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Different Traits Affect Salinity and Drought Tolerance during Germination of *Citrullus colocynthis*, a Potential Cash Crop in Arid Lands

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Abstract: *Citrullus colocynthis*, a native plant with potential uses as a feedstock for edible oil, biodiesel, and animal feed make it a potential cash crop. The importance of propagating this species under saline arid habitats necessitates understanding environmental factors affecting salinity and drought tolerance during the germination stage. Here, we assessed the impacts of seed collection time, the temperature of incubation on salinity, and drought tolerance during the seed germination stage of different accessions growing in the botanical garden of the University of Sharjah. No previous study assessed the interactive effects of these factors on the drought and salinity tolerance of this species. Three accessions (9, 10, and 13) differed in fruit and seed size and color, and germination behavior, and were selected from an earlier study. Seeds that matured in summer and winter on these accessions were treated with three salinities (0, 50, and 100 mM NaCl), and PEG levels (0, −0.3, and −0.6 MPa) and incubated at two temperatures (20/30 and 25/35 °C). The results showed significant effects of all factors (collection time, temperature, drought, and salinity) and their interactions on germination percentage. Seeds of *C. colocynthis* were very sensitive to salinity and drought stress, and the sensitivity depended on the time of seed collection, accession, and incubation temperature. The overall germination and tolerance to salinity and drought were significantly greater in seeds of accession 10, seeds that matured in summer, and seeds incubated at 25/35 °C. The germination in NaCl solutions was greater than in PEG solutions, indicating that seed germination was more sensitive to osmotic stress created by PEG than NaCl. Moreover, when transferred from NaCl, the recovery of ungerminated seeds was greater than in PEG solutions. This result indicates that the detrimental effect of salinity in *C. colocynthis* could be mainly attributed to osmotic rather than ion-toxicity effects. To adopt *C. colocynthis* as a cash crop or to restore degraded desert habitats, it is recommended to use seeds of drought- and salt-tolerant accessions (e.g., 10), especially those that mature in summer.

Keywords: *Citrullus colocynthis* accessions; drought tolerance; germination recovery; incubation temperature; salinity tolerance; seed dormancy; seed maturation time

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1. Introduction

Deserts face several environmental challenges for seedling establishment and plant survival [1,2]. Seed germination and seedling establishment are among the critical sensitive stages in the life cycle of plants in arid deserts. Environmental conditions at the germination bed, e.g., temperature, light, moisture content, and salinity, interact to control germination level and time, determining the time of seedling emergence and establishment success.

Under the arid conditions of the deserts, drought and salinity are considered the most influential environmental factors affecting seed germination and plant growth. Water availability is among the main environmental factors controlling desert plants' success. The germination process starts with water imbibition; therefore, water is the most important environmental factor controlling seedling emergence [3]. Seeds of every species need a specific water threshold for starting the germination process. Seeds stay dormant or enter an induced dormancy when the soil moisture content is under that threshold [4,5]. The moisture threshold that stimulates germination is species- and habitat-specific.

In general, plants in arid environments can start germination at lower water potentials than plants in wet habitats [4,6]. In addition, desert plants vary greatly in their water requirements for starting germination [7]. For example, several plant species from the Siziwang Desert Steppe, China (*Lagochilus ilicifolium*, *Allium polyrhizum*, *Linum stelleroides*, *Stipa breviflora*, *Allium tenuissimum*, *Haplophyllum dauricum*, *Plantago depressa*, *Artemisia sieversiana*, *Potentilla multicaulis*, *Artemisia frigida*, and *Artemisia mongolic*) germinated to very low levels in a relatively higher water potential (−0.87 MPa PEG) [7]. However, other species (e.g., *Allenrolfea occidentalis*) germinated in a very low water potential (−4 MPa PEG) [8].

Salinity is another important abiotic stress challenging seed germination, and seedling establishment, especially in the salt-sensitive glycophytes of arid deserts [9]. Unlike halophytes, seeds of glycophytes tolerate little salinity and cannot maintain their viability in saline solutions, i.e., seeds have lower recovery when transferred from saline solutions to distilled water [10]. As in drought, salinity controls germination by reducing the osmotic potential and limiting the imbibition process. Whereas drought affects germination through osmotic effects, the effect of salinity is through osmotic potential and/or ions' toxicity, especially Na^+ and Cl^- [11]. Moreover, the temperature during seed incubation is another factor that interacts with soil moisture and salinity to regulate germination in arid deserts [12,13]. The interaction between salinity and soil moisture with temperature can determine the proper seed germination time, determining the subsequent seedling establishment and survival under field conditions [10]. Several studies have assessed the interactive effect of salinity and water deficit with temperatures on the germination behavior of salt-tolerant plants. However, few studies have been done on glycophytes. For example, the detrimental effect of salinity is exacerbated at both high and low temperatures but generally less severe at optimum temperatures [14,15]. Similarly, higher temperatures increased the detrimental effect of water deficit in several glycophytic plants [16,17].

Citrullus colocynthis is a xerophytic native desert plant with economic and ecologic importance. It adopts several physiological, biochemical, and morphological mechanisms to tolerate the harsh conditions of hot arid deserts, especially water scarcity and high temperatures. However, it is considered salt-sensitive (i.e., glycophyte). This plant produces bioactive compounds with several medicinal properties, such as anti-inflammatory, hypoglycemic, hepato-protective, cure for digestive disorders, antidiabetic, antimicrobial, anticancer, antioxidant, analgesic, hypolipidemic, antineoplastic, anti-allergic, and hypolipidemic agent, which make it used in folk medicine [18–22]. In addition, *C. colocynthis* seeds are also a viable feedstock for edible oil and biodiesel production due to their greater oil content [23,24]. The fatty acid oil profile and biodiesel properties of *C. colocynthis* are similar to the oil profiles of sunflower, soybean, and safflower oil [23,24]. In addition, the seed chemical composition of *C. colocynthis* makes it a potential source of animal feed [25]. Seeds are rich in oil and protein, with special types of fatty acids and amino acids. The globulin contributed 66.1% of the total seed protein [26]. These economic benefits suggest that *C. colocynthis* could be a potential cash crop in marginal desert habitats, where few conventional crops could grow [27]. Qasim classified *C. colocynthis* as a cash crop that could grow with brackish water in marginal desert lands [28].

Citrullus colocynthis has several features of ecological importance, including sand dune fixation and enhancing species biodiversity. The creeping nature of this plant enables it to fix the dunes and combat land erosion and desertification [29]. Moreover, *C. colocyn-*

this accumulates sand, making nebkha dunes that facilitate the establishment of other herbaceous and shrubby plants. The role of *C. colocynthis* as a nurse plant can increase biodiversity and combat desertification in mobile, nutrient-poor sandy deserts [30,31]. The ecological and economic importance of *C. colocynthis* and its ability to tolerate drought and heat stress make this plant a potential cash crop grown in marginal lands in arid regions [32,33]. Understanding environmental abiotic stress impacting seed germination and seedling establishment of *C. colocynthis* should be considered when adopting it as an economic cash crop with potential medicinal properties and biofuel production.

Seeds of *C. colocynthis* showed great variation in dormancy levels in different geographical regions of the world. For example, only around 5% germinated in seeds from an Iranian desert population [34]. Similarly, there was a deep dormancy (i.e., no germination) in seeds of 30 accessions of *C. colocynthis* collected from different locations in the UAE [35]. Moreover, Bano and Singh reported no germination in another 30 accessions from India [36]. Furthermore, seeds collected from the Negev desert did not germinate under different soaking treatments [37]. However, manual scarification followed by soaking for 48 h and incubation at 30 °C resulted in full germination within 48 h for seeds collected from different accessions of the UAE [35] and India [36]. In addition, the dormant seeds germinated to 67% after manual scarification with sandpaper [34]. The deep dormancy of *C. colocynthis* was defined as physical dormancy due to the hard seed coat and physiological dormancy due to certain inhibitory substances in the inner seed membrane [35]. In addition, Koller attributed the deep dormancy in seeds from the Negev deserts to the inner membrane [37]. Interestingly, the dormancy of seeds from the UAE desert depended on accessions and the time of fruit maturation [38–40].

Several studies assessed the drought tolerance of *Citrullus* spp. (e.g., *C. colocynthis* [35,41] and *C. lanatus* [42]). In *C. colocynthis,* there was a significant reduction in the germination rate with increased drought and salinity stress levels [35,41]. For example, the salinity assessment on seed germination of thirty accessions of *C. colocynthis* collected from different habitats of the UAE indicated that the germination was very sensitive to salinity; germination was reduced by 95–100 of that in control at 100 mM NaCl [35]. Those authors reported variations in salt tolerance among different accessions collected from different habitats. Similarly, the germination of Iranian seeds was significantly decreased in −1.2 MPa PEG and 100 mM NaCl; no germination was reported at the −1.5 MPa and 210 mM NaCl treatments [41]. The response to salinity treatments varied between the different accessions; some accessions were relatively tolerant to salinity, while others were sensitive [35,41]. Although earlier studies assessed the drought and salinity tolerance on seed germination of *C. colocynthis*, no study assessed the interactive effects of environmental factors prevailing around maternal plants during seed development, genetic identity (accession), and temperature of incubation on drought and salinity tolerance of *C. colocynthis*. According to our knowledge, our study is among a few studies that assessed the interactive effect of time of fruit maturation, accession, and temperature of incubation on salinity and drought tolerance of glycophytic plants and the first that does that on the important native *C. colocynthis*. Al-Nablsi concluded that the variations in *C. colocynthis* germination among seeds of different geographical regions could be genetically based and/or environmentally induced [40]. Selection of quality seeds based on the accession and time of seed maturation would help the propagation of this important cash crop in marginal dry and salty deserts.

Al-Nablsi reported genetic diversity among 12 accessions from one *C. colocynthis* population in the UAE [40]. The genetically differed accessions also varied in fruit size, color, stripe pattern, and seed size and color. Seeds of the different accessions varied significantly in dormancy levels and germination requirements [40]. Moreover, seeds' phenolic and flavonoid contents and antioxidant activity from three accessions depended significantly on seed collection time and accession. Furthermore, the GC-MS metabolic profile showed unique phytochemicals in seeds of a specific accession collected at a specific time of the year [43]. Therefore, we hypothesize that seed collection time and accession could affect the salinity and drought tolerance of *C. colocynthis* during seed germination.

The present study aimed to assess the impacts of seed collection time (summer vs. winter) and temperature of incubation conditions on salinity and drought tolerance during the seed germination stage for different accessions grown in the botanical garden of the University of Sharjah. The study results will help define the proper environmental conditions and accession that produce the highest seed quality, i.e., tolerate higher salinity, drought, and temperatures during germination. Seeds of high tolerance to stress conditions of a specific accession could be used when adopting this plant as a cash crop to grow in the marginal hot deserts of the Arab Gulf region.

2. Results

2.1. Salinity Tolerance

2.1.1. Final Germination

All main factors of seed quality (season of collections and accession) and incubation conditions (temperature and NaCl concentration) and most of their interactions had significant effects ($p < 0.05$) on the final germination of *C. colocynthis* germination (Table 1). The overall germination in the different salinity levels was significantly greater in summer than in winter seeds; it was greater in summer than in winter by 52%, 72.1%, and 31.6% in 0, 50, and 100 mM NaCl, respectively. Similarly, the overall germination and salinity tolerance were significantly greater at higher than lower temperatures. The final germination decreased from 68.9%, 40.0%, and 10.9% in 0, 50, and 100 mM NaCl, respectively, at 25/35 °C to 44.1%, 13.0%, and 0.2%, respectively, at 20/30 °C. Furthermore, germination and salinity tolerance of accession 10 were significantly greater than in accessions 9 and 13 (Figure 1). Regardless of the season and incubation temperature, the final germination of accession 10 was greater than that of accession 9 by 16.2%, 84.4%, and 90.9% in 0, 50, and 100 mM NaCl, respectively, and greater than accession 13 by 63.0%, 164.4%, and 41.2%.

Table 1. Effects of time of collection (season), accession, the temperature of incubation, and salinity (NaCl) on final germination, germination rate index, and germination recovery of *Citrullus colocynthis* seeds.

	df	Final Germination			Germination Rate Index			Germination Recovery		
		Ms	F-Ratio	*p*	Ms	F-Ratio	*p*	Ms	F-Ratio	*p*
Season (S)	1	0.882	117.836	<0.001	241.23	6.987	<0.05	0.029	15.535	<0.001
Accession (A)	2	0.581	77.578	<0.001	608.0	17.609	<0.001	0.013	6.871	<0.01
Temperature (T)	1	2.271	303.461	<0.001	2915.1	84.428	<0.001	0.014	7.720	<0.01
NaCl	2	4.219	563.858	<0.001	4731.0	137.022	<0.001	0.579	311.4	<0.001
S*A	2	0.528	70.537	<0.001	299.74	8.681	<0.001	0.006	3.460	<0.05
S*T	1	0.075	10.041	<0.01	3.712	0.108	ns	0.004	2.199	ns
S*NaCl	2	0.256	34.212	<0.001	13.274	0.384	ns	0.010	5.548	<0.01
A*T	2	0.165	22.020	<0.001	87.978	2.548	ns	0.002	1.314	ns
A*NaCl	4	0.154	20.533	<0.001	42.200	1.222	ns	0.006	2.986	<0.05
T*NaCl	2	0.231	30.811	<0.001	702.4	20.344	<0.001	0.019	9.990	<0.001
S*A*T	2	0.066	8.878	<0.001	95.77	2.774	ns	0.003	1.553	ns
S*A*NaCl	4	0.116	15.549	<0.001	42.08	1.219	ns	0.004	2.222	ns
S*T*NaCl	2	0.017	2.253	ns	3.23	0.093	ns	0.000	0.163	ns
A*T*NaCl	4	0.042	5.624	<0.001	75.65	2.191	ns	0.001	0.616	ns
S*A*T*NaCl	4	0.027	3.594	<0.01	65.95	1.910	ns	0.002	1.216	ns
Error	102	0.007			34.528			0.002		

ns: statistically insignificant at $p \leq 0.05$.

The salinity tolerance depended on the accession and temperature of incubation; the interaction between accession, temperature, and NaCl concentration was significant ($p < 0.001$, Table 1). For example, final germination of 9, 10, and 13 accessions, regardless of the season, was greater at 25/35 °C than at 20/30 °C by 73.8%, 48.7%, and 47.3%, respectively, in non-saline-treated seeds, but by 200%, 221.4%, and 192%, in 50 mM NaCl. Moreover, in 100 mM NaCl, almost no germination occurred at 20/30 °C, but overall

germination of the two seasons reached 7.9%, 15%, and 10% in accessions 9, 10, and 13, respectively (Figure 1).

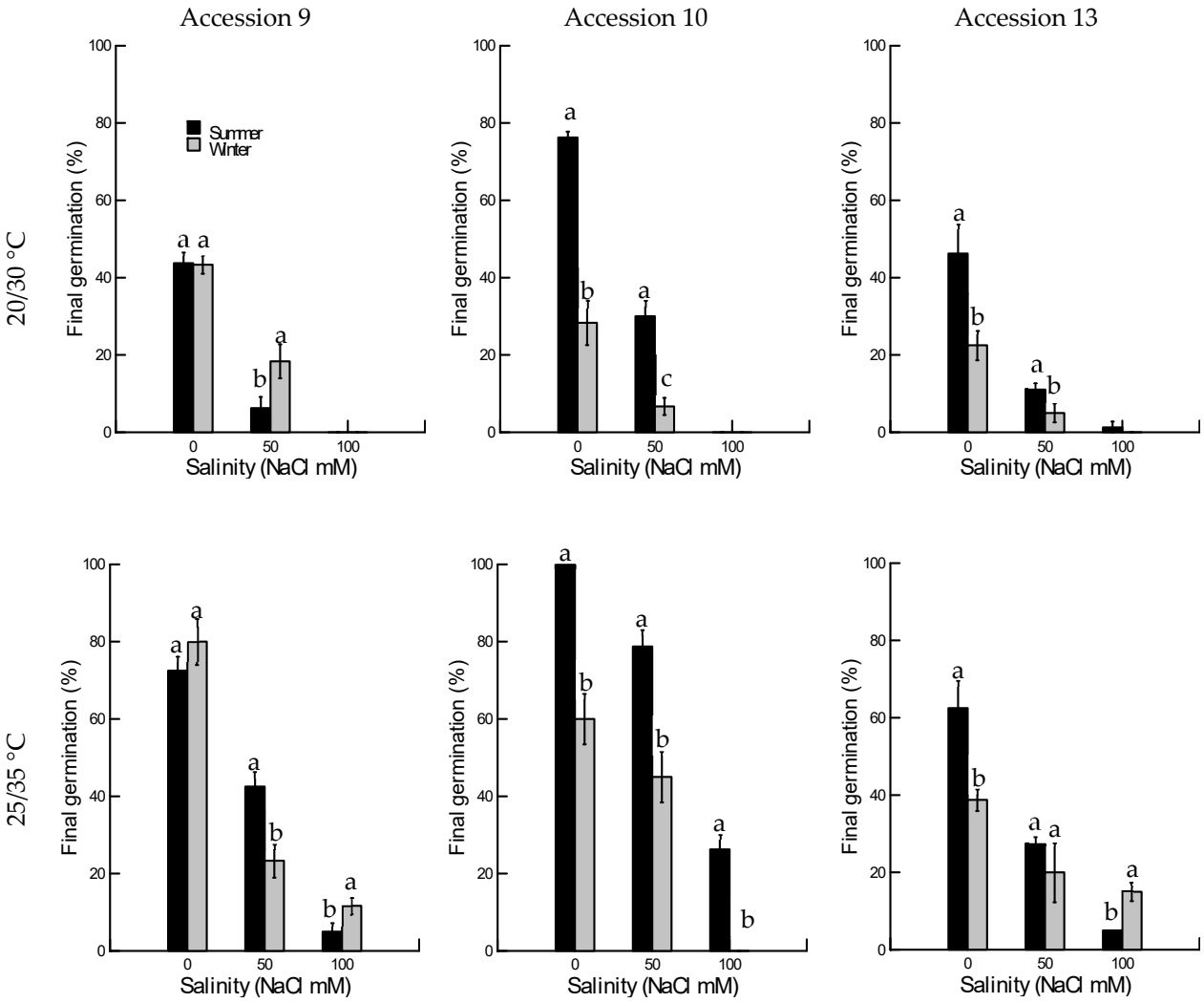


Figure 1. Effects of the accession, seed maturation season, and temperature of seed incubation on salinity tolerance during germination of *Citrullus colocynthis* seeds. Means of summer and winter with the same letter do not differ significantly at $p \leq 0.05$.

The interaction between main factors (accession, collection season, incubation temperature, and NaCl concentration) was significant ($p < 0.01$, Table 1), indicating that final germination in non-saline-treated seeds (control) and salinity tolerance depended on accession, season, and temperature (Figure 1). In accession 9, there was no significant difference between summer and winter seeds at both 20/25 and 25/35 °C for seeds germinated in distilled water. In 50 mM NaCl, the final germination of winter seeds of accession 9 was greater than that of summer seeds at 20/25 °C, but the reverse was true at 25/35 °C. In 100 mM NaCl, winter seeds of the same accession germinated more than summer seeds at higher temperatures, but no germination occurred at the lower temperatures. In accessions 10 and 13, the final germination was significantly greater for summer than winter seeds (Figure 1).

2.1.2. Germination Rate Index

The ANOVA showed significant effects for the main factors (season of collections, accession, temperature, and NaCl concentration) on the germination rate index ($p < 0.05$,

Table 1). Germination was generally faster in distilled water than in saline solutions and in 50 mM than 100 mM NaCl (Figure 2). Moreover, the germination was faster for seeds that matured in summer than in winter and at higher (25/35 °C) than lower (20/30 °C) temperatures. The overall GRI was significantly greater in accession 13 (25.2) than in accession 10 (18.5) and 9 (20.9). The interaction between salinity and temperature was significant, indicating that GRI depended on the temperature of seed incubation. There was no significant difference in GRI of non-saline-treated seeds at 20/30 and 25/35 °C. However, GRI was significantly greater in 50 and 100 mM NaCl at 25/35 °C (28.2 and 19.6, respectively) than at 20/30 °C (20.2 and 1.4, respectively) (Figure 2).

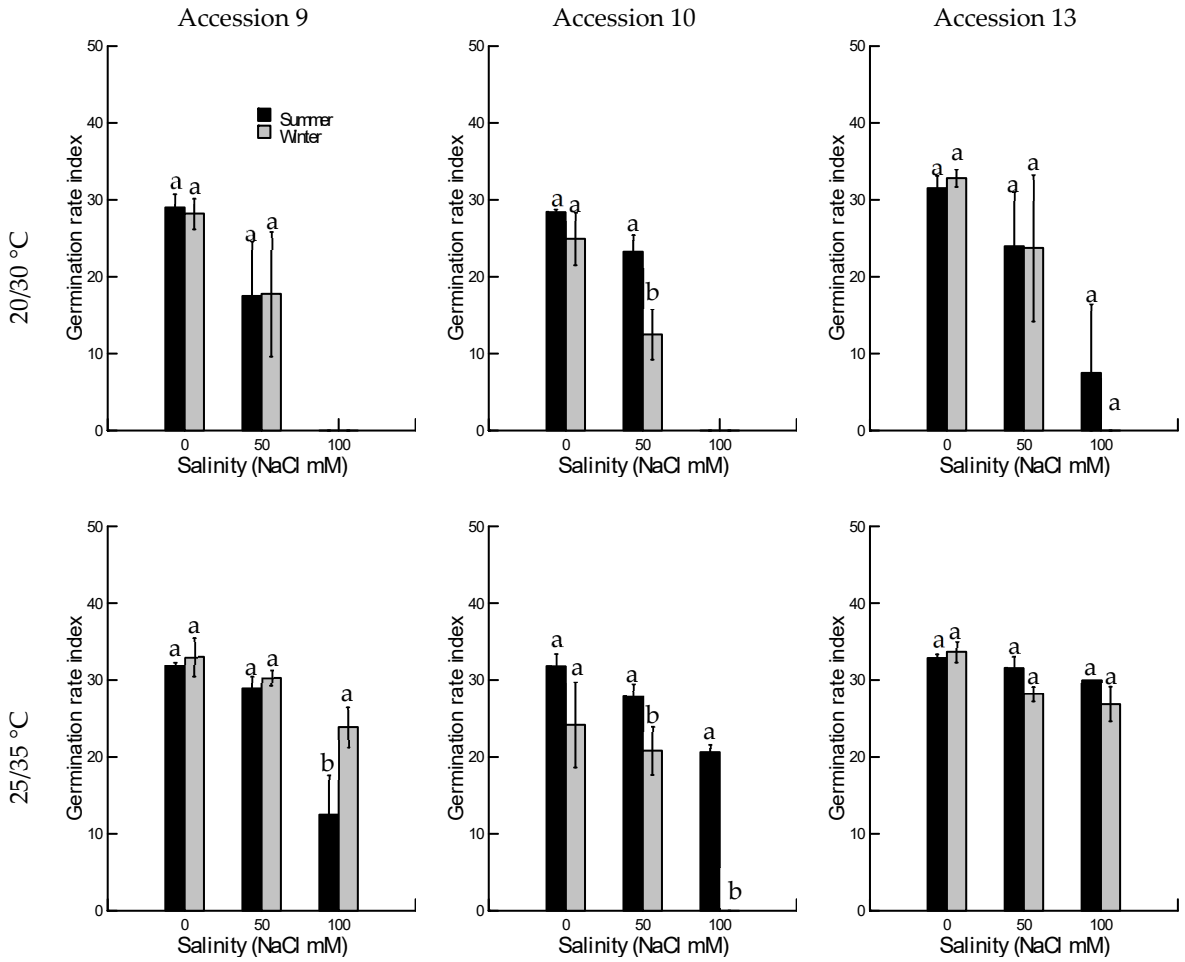


Figure 2. Effects of the accession, seed maturation season, and temperature of seed incubation on salinity tolerance during germination of *Citrullus colocynthis* seeds. Means of summer and winter with the same letter do not differ significantly at $p \leq 0.05$.

2.1.3. Germination Recovery

The main factors (season of collections, accession, temperature, and NaCl concentration) showed significant effects on germination recovery ($p < 0.01$, Table 1). Similar to final germination, overall germination recovery was significantly greater for seeds collected in summer and incubated at 25/35 °C than those collected in winter and incubated at 20/30 °C. In addition, the interactions between NaCl with the accession, temperature, and season of seed collection were significant, indicating that germination recovery depended on these factors individually. For example, there was no significant difference in germination recovery of seeds that failed to germinate in 50 mM NaCl at 20/30 and 25/35 °C. However, germination recovery was significantly greater in 100 mM NaCl at 25/35 °C (26.7%) than at 20/30 °C (19.9%). Similarly, germination recovery of summer and winter seeds did not

differ in 50 mM NaCl, but the recovery was significantly greater for summer than winter seeds in 100 mM NaCl. Like final germination, germination recovery was significantly greater for seeds of accession 10 than those of 13 and 9, but the difference was greater in the former than in the latter accession (Figure 3).

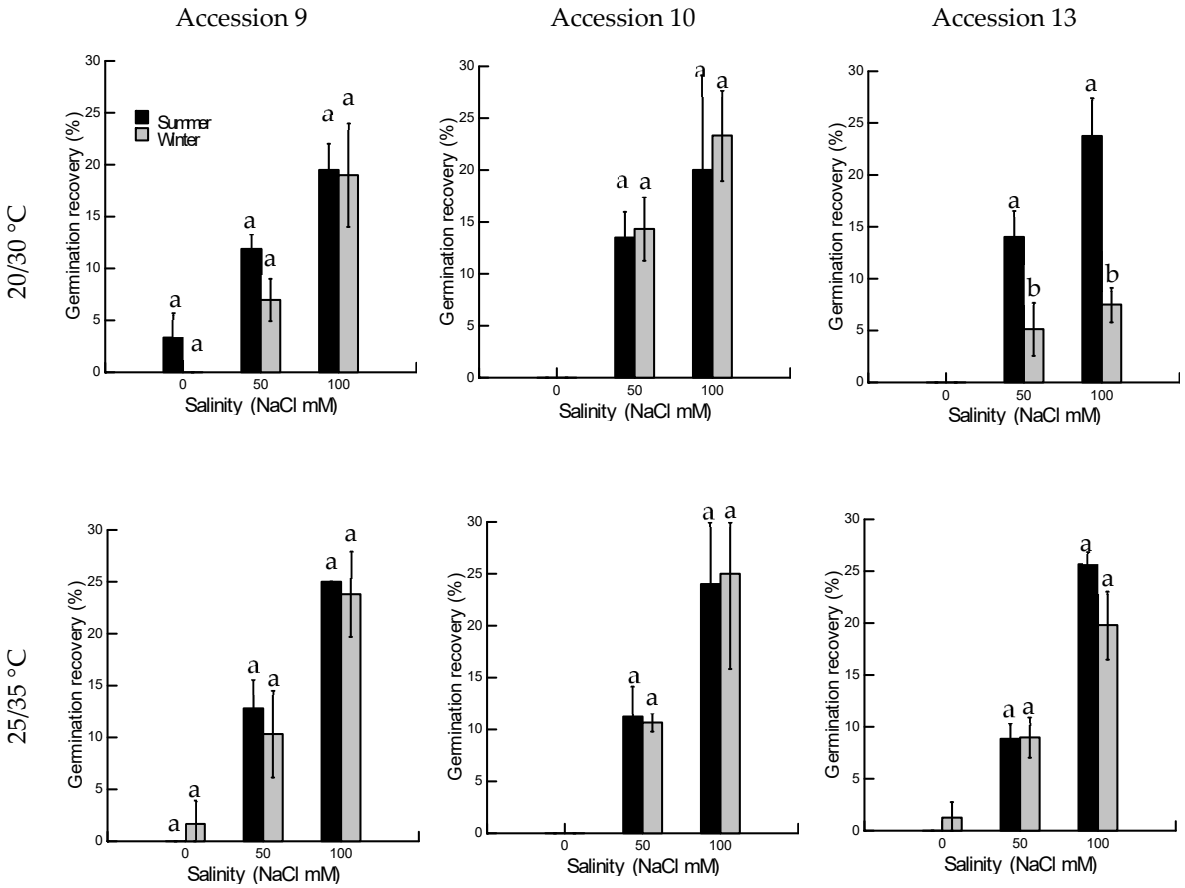


Figure 3. Effects of the accession, seed maturation season, and temperature of seed incubation on germination recovery of *Citrullus colocynthis* seeds transferred from different saline solutions to distilled water. Means of summer and winter with the same letter do not differ significantly at $p \leq 0.05$.

2.2. Drought Tolerance

2.2.1. Final Germination

The results showed the lower ability of *C. colocynthis* seeds to germinate in PEG solution than NaCl. There were significant effects for all main factors and most of their interactions ($p < 0.05$, Table 2) on drought tolerance of *C. colocynthis* seeds. Drought tolerance was greater for accessions 9 and 10 seeds collected in summer and germinated at higher temperatures (25/35 °C) than those collected in winter and at lower temperatures (20/30 °C). In general, no germination occurred in −0.6 MPa PEG in all accessions at both temperatures. In −0.3 mM PEG, the final germination at 25/35 °C was 3.3- and 2.56-folds higher than at 20/30 °C for accessions 9 and 10 collected in summer and 1.33 for accession 9 collected in winter. Seeds of accessions 10 and 13 collected in winter did not germinate at 20/30 °C but germinated to 6.7% and 2.5% at 25/35 °C, respectively. Similarly, the tolerance to −0.3 MPa PEG in 25/35 °C was greater for accessions 9, 10, and 13 seeds collected in summer than those collected in winter by 1.88-, 4.33-, and 2-folds. In the same PEG concentration, summer seeds of accessions 10 and 13 germinated at 20/30 °C to 11.3% and 10%, but winter seeds of the same accession did not germinate (Figure 4).

Table 2. Effects of time of collection (season), accession, the temperature of incubation, and drought (simulated by PEG) on final germination and germination recovery of *Citrullus colocynthis* seeds.

	df	Final Germination			Germination Recovery		
		Ms	F-Ratio	*p*	Ms	F-Ratio	*p*
Season (S)	1	0.589	127.040	<0.001	0.000	0.011	ns
Accession (A)	2	0.280	60.320	<0.001	0.000	0.116	ns
Temperature (T)	1	0.706	152.163	<0.001	0.001	1.465	ns
PEG	2	5.864	1263.792	<0.001	0.099	210.780	<0.001
S*A	2	0.286	61.597	<0.001	0.001	1.761	ns
S*T	1	0.010	2.130	ns	0.000	0.565	ns
S*PEG	2	0.302	65.024	<0.001	0.000	0.052	ns
A*T	2	0.078	16.880	<0.001	0.001	2.142	ns
A*PEG	4	0.172	37.121	<0.001	0.004	7.809	<0.001
T*PEG	2	0.492	105.938	<0.001	0.000	0.722	ns
S*A*T	2	0.028	6.024	<0.01	0.000	0.114	ns
S*A*PEG	4	0.183	39.519	<0.001	0.001	1.571	ns
S*T*PEG	2	0.003	0.686	ns	0.001	1.178	ns
A*T*PEG	4	0.034	7.305	<0.001	0.001	1.216	ns
S*A*T*PEG	4	0.020	4.368	<0.01	0.001	1.998	ns
Error	102	0.005			0.000		

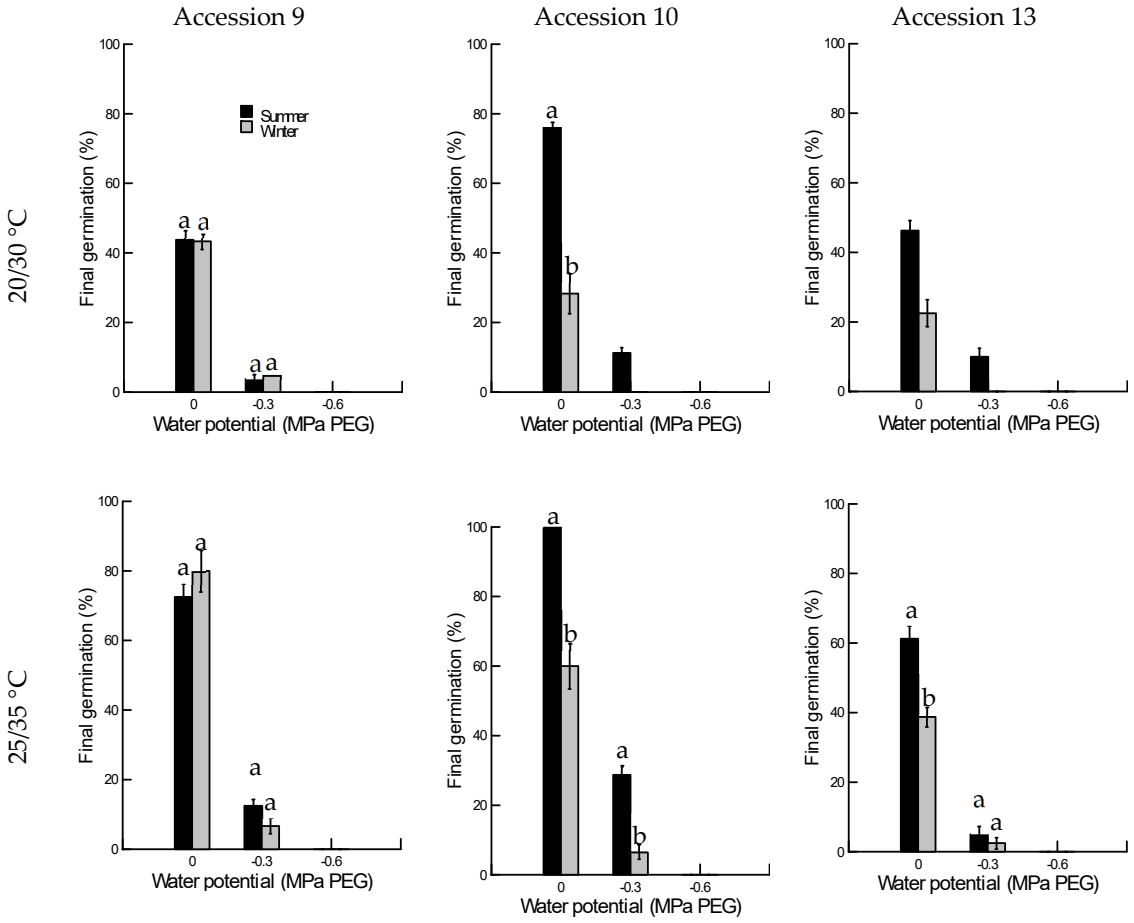


Figure 4. Effects of the accession, seed maturation season, and temperature of seed incubation on drought tolerance, as simulated by PEG, during germination of *Citrullus colocynthis* seeds. Means of summer and winter with the same letter do not differ significantly at $p \leq 0.05$.

2.2.2. Germination Recovery

The ability of *C. colocynthis* seeds to recover their germination when transferred from PEG solutions to distilled water was less than their recovery from NaCl solutions (Figures 3 and 5). The only significant effect on germination recovery was PEG concentration and the interaction between the accession and PEG concentration. The recovery from −0.3 MPa PEG was greater than from −0.6 MPa PEG. In addition, the recovery of accession 10 seeds was greater than that of accessions 9 and 13. The recovery germination of accessions 10, 9, and 13 seeds was 11.6%, 9.6%, and 8.0%, respectively, from −0.3 MPa PEG, and 4.6%, 6.0%, and 8.0%, respectively from −0.6 MPa PEG (Figure 5).

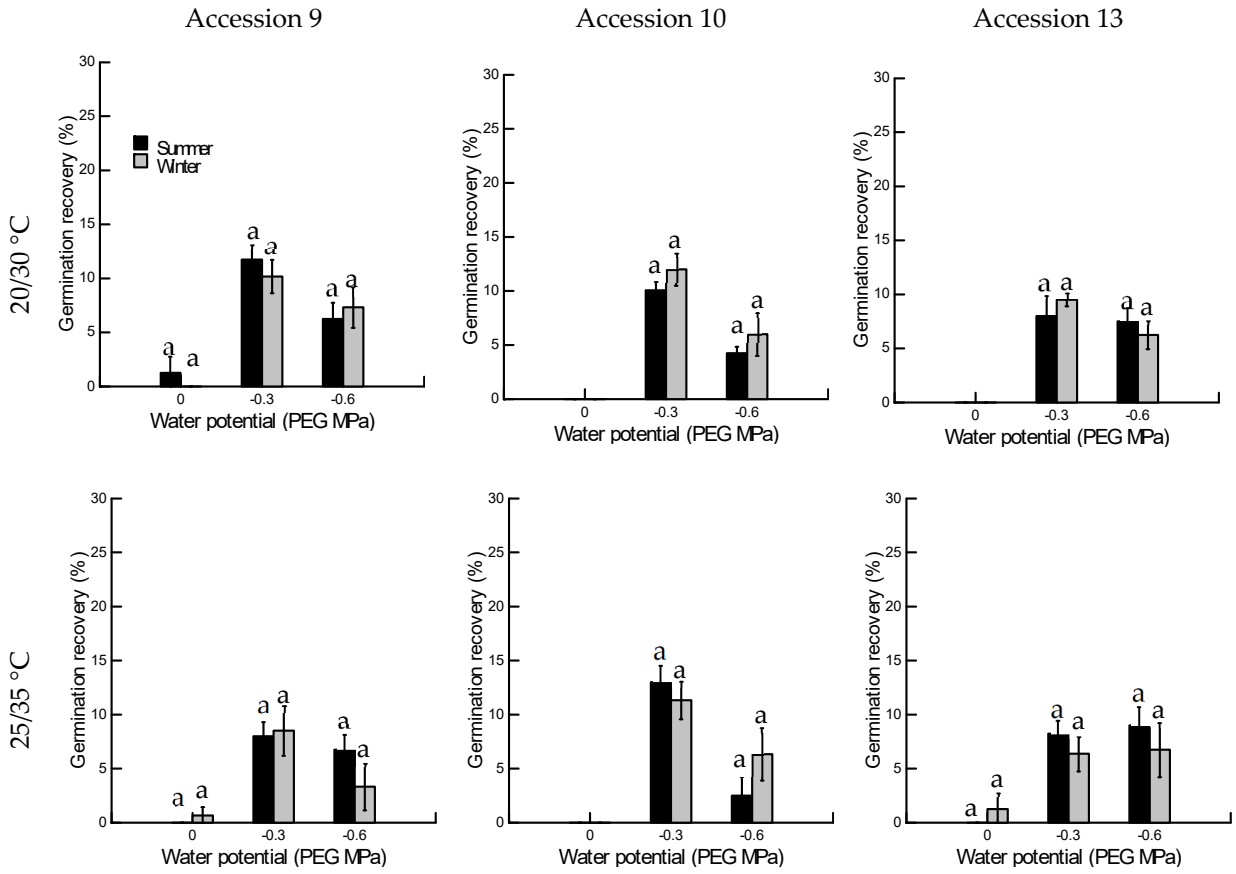


Figure 5. Effects of the accession, seed maturation season, and temperature of seed incubation on germination recovery (%) of *Citrullus colocynthis* seeds after their transfer from different PEG levels.

3. Discussion

Several studies reported deep dormancy in *C. colocynthis* [34,35,37]. This dormancy was broken with scarifications [34], storage [38,44], and removal of the inner seed membrane [37]. However, El-Keblawy reported that the *C. colocynthis* dormancy is controlled by environmental conditions prevailing during seed development and maturation; seeds that matured in winter were almost dormant, and seeds that matured at other times of the year germinated to 100% under specific light and temperature conditions [38,39]. The results of our study indicate that seed dormancy in *C. colocynthis* depended on the accession, season of fruit collection, and incubation temperature. For example, accession 10 seeds matured in summer germinated to 100% at 25/35 °C in distilled water, but seeds of accession 9 and 13 germinated to 20–40%. Interestingly, a comparison of the germination of the three accessions of the present study with that of their maternal plants in Al-Nablsi [40] indicates that seed dormancy in *C. colocynthis* is an inheritable trait. Seeds of maternal plants of accessions 10, 13, and 9 collected from natural habitats in early December (i.e., matured in

November) germinated to 97%, 65%, and 37%, respectively, at 25/35 °C in light. This result is comparable to the germination of the first generation of the same accessions [40].

It has been documented that environmental conditions prevailing during seed development and maturation affect dormancy level and germination tolerance to environmental stresses. Our results indicated that seeds collected in summer germinated to higher levels and tolerated more salinity and drought than seeds matured in winter. Moreover, summer seeds recovered their germination to higher levels when transferred from PEG solutions to distilled water than winter seeds. Similarly, seeds of *Arabidopsis thaliana* that matured at higher temperatures germinated to higher levels and tolerated lower osmotic potential than seeds that matured at lower temperatures [45]. Khan and Gul reviewed salinity tolerance in halophytes of Pakistan's hot subtropical maritime deserts and the cooler Great Basin Desert. They concluded that salinity tolerance was higher in seeds of the former than in the latter halophytes [46]. It has been reported that environmental conditions prevailing during seed maturation can affect seed chemical composition, affecting seed metabolic processes and seed coat structure and thickness [47–49]. Recently, Al-Nablasi reported significantly higher free radical scavenging activity (i.e., antioxidant activity) in summer seeds than in winter seeds of *C. colocynthis*. In addition, the number of metabolites with antioxidant activities was significantly greater in summer seeds (27 compounds) than in winter seeds (17 compounds). Such results might explain summer's higher germination, salinity, and drought tolerances than winter seeds [43].

Our results showed that seeds of *C. colocynthis* were very sensitive to salinity and drought stress, and the sensitivity depended on the accession. The salinity tolerance of accession 10 was significantly greater than in accessions 9 and 13 (Figure 1). Regardless of the season and incubation temperature, the final germination of accession 10 was greater than that of accession 9 by 84.4% and 90.9% in 50 and 100 mM NaCl, respectively, and more than that of accession 13 by 164.4% and 41.2%. Similarly, the germination level and salinity tolerance varied between different *C. colocynthis* accessions were collected from different geographical regions in the UAE [35], India [36], and Iran [41]. In the Indian and UAE populations, seeds were more tolerant to salinity than Iranian seeds. For example, in the UAE and Indian populations, some accessions did not germinate in 50 and 100 mM NaCl, but others germinated to up to 90% and 5% in the same NaCl concentration [35,36]. However, two Iranian genotypes germinated to 20% and 8% in 150 mM NaCl [41]. In all of these studies, the accessions/genotypes experienced different environmental conditions prevailing in different geographical regions. However, the accessions in our study were grown in a botanical garden under the same environmental conditions, indicating a genetic base rather than an environmentally induced variation in the germination level and stress tolerance of the different accessions.

The chemical compositions in the seeds of the different accessions might explain the difference in germination level and stress tolerance between the different accessions [43]. The free radical scavenging activity and the number of metabolites with antioxidant activity were greater in accession 10 seeds than in seeds of the other accessions [43]. This further explains the higher germination and greater salinity and drought tolerance of accession 10 seeds than the other accessions. Antioxidants regulate reactive oxygen species (ROS) to be within the permissive level (i.e., the oxidative window for germination) [50]. The increase in the antioxidant enzymes under salinity and drought stress is necessary to reduce ROS accumulation and its oxidative damage [51]. Several studies have shown that seed sources affect salt tolerance in several species [31,52–55]. Those authors recommended using salt-tolerant seeds in the restoration of salt-affected lands. Our results indicate that seeds of salt-tolerant accessions, such as 10, should be adopted to use *C. colocynthis* as a cash crop or restore salt-affected soils.

The soil's water potential controls the time of seedling emergence, determining the fate of seedling establishment and survival [53,56]. The present study showed low tolerance to water deficiency simulated by PEG; no *C. colocynthis* seeds germinated in −0.6 MPa PEG. In addition, few seeds recovered their germination when transferred from PEG solutions to

distilled water, indicating low tolerance to even high osmotic potential (−0.6 MPa PEG). However, seeds of an Iranian population tolerated lower osmotic potentials; about 20% and 10% of the seeds germinated in −0.9 and −1.2 MPa PEG, respectively [41]. In addition, it has been reported that the germination of other cucurbits was also sensitive to the lower osmotic potential. For example, Thanos and Mitrakos reported that the germination of intact watermelon seeds was almost inhibited at −0.74 MPa [57]. Based on the present study, *C. colocynthis* could be considered more drought-sensitive during germination than *C. colocynthis* in the Iranian population and other cultivated cucurbits such as watermelon. Furthermore, it seems that seeds of *C. colocynthis* are more drought-sensitive than several other desert plants that tolerate lower osmotic potentials, such as *Allenrolfea occidentalis* (−4 MPa) [8], *Prosopis juliflora*, and *P. pallida* (−1.5 MPa) [13,58], *Haloxylon ammodendron* (−3 MPa) [59], *Salsola imbricata* (−2.2 MPa) [53], *P. flexuosa* and *P. chilensis* (−1.4 MPa) [60], and *Suaeda vermiculata* (−1.0 MPa) [54]. The sensitivity of *C. colocynthis* to water deficit during germination indicates that its seeds would not germinate in years receiving rainfall lower than average. In addition, *C. colocynthis* might be affected more by the global warming scenario that will be associated with more drought in the Arabian Peninsula [61]. However, germination of *C. colocynthis* can occur even in dry years in low-lying lands and areas exposed to water floods, precisely where this species is common in the natural habitats [40]. Moreover, *C. colocynthis* grows on sand dunes that absorb and hold water for longer times, allowing seed germination even in years receiving less than average rainfall.

It has been proposed that saline solutions affect seed germination either to a lower osmotic potential effect that hinders water imbibition or the accumulation of toxic ions that disturb ion hemostasis and essential cellular metabolic activities. However, the negative drought effect simulated by PEG results mainly from the lower osmotic potential [62]. Therefore, it has been proposed that the detrimental effect of salinity is greater than iso-osmotic PEG [13,63]. In our study, however, the detrimental effect of PEG was greater than NaCl; few seeds of *C. colocynthis* germinated in −0.3 MPa PEG, but considerable proportions germinated in 100 mM NaCl (around −0.5 MPa). Moreover, the germination recovery of ungerminated seeds was greater from saline than PEG solutions. Such results indicate that the detrimental effect of salinity in *C. colocynthis* could not be attributed to ion-toxicity but to osmotic effects. The detrimental effect of the iso-osmotic solution was greater than NaCl in several other desert species, including *Henophyton deserti* [64], *Suaeda vermiculata* [1,54], and *Haloxylon stocksi* [65]. The relatively lesser effect of NaCl, as compared to PEG, indicates that seeds might probably minimize the toxicity effect of sodium ions on the cytosol through its accumulation in central vacuoles [66]. However, the desiccation resulting from PEG treatment could disrupt the membrane that affects organelle morphology and function [67]. The result also indicates that water is the most important limiting factor for the seedling emergence and recruitment of *C. colocynthis* in the hyper-arid hot Arabian deserts.

Appropriate temperature is the most important factor in regulating germination in the cucurbit family [68]. Our results indicate that *C. colocynthis* germination was significantly greater at higher temperatures (25/35 °C) than at moderate temperatures (20/30 °C). We recorded little germination at 15/25 °C, especially in the different PEG and NaCl concentrations; therefore, we did not include the results. These results are consistent with our earlier studies [33–35]. Interestingly, the present study results indicate that tolerance of *C. colocynthis* to salinity and drought was greater at higher (25/35 °C) than at moderate temperatures (20/30 °C). A similar result was reported in *Cyprus conglomeratus*, another sand dune glycophyte in the Arabian deserts [14]. However, other studies reported higher salinity tolerance at moderate temperatures in other desert glycophytes, such as *Salsola imbricata* [64] and *Haloxylon salicornicum* [69]. Although seed germination of *C. colocynthis* was drought-sensitive, the vegetative plants are very tolerant to drought and high temperatures [64]. Si et al. [70] confirmed the presence of 18 genes in root tissues involved in various abiotic and biotic stress tolerance, including drought and high temperatures. Among these are two heat shock protein genes that help plants, and maybe seeds, tolerate

high temperatures. Similarly, Wang reported the presence of several transcripts involved in salinity, drought, and heat tolerance in *C. colocynthis* [71]. Interestingly, we recorded soil temperature under the *C. colocynthis* canopy using a thermal camera of up to 71 °C and tissue temperature above 55 °C [Ali El-Keblawy, unpublished data].

4. Materials and Methods

4.1. Accession Selection and Growth Conditions

This study used seeds of three accessions (9, 10, and 13) of Al-Nablsi [40]. These accessions showed high genetic diversity. In addition, the seed size and color, fruit size, weight, and color vary greatly among the different accessions. Seeds of accessions 10 and 13 were larger (3.07 g/100 seeds) with a brown color than those of accession 9 (2.2 g/100 seeds) with a dark brown color. In addition, the fruit circumference of accessions 10 and 13 was larger (29.26 and 28.05 cm, respectively) and their weight was heavier (212.2 and 181.8 g, respectively) than accession 9 (fruit circumference = 23.0 cm and the weight of 100 seeds = 2.2 g) [40]. Furthermore, the pattern of stripes on the rind varies among the different accessions (Figure 6).

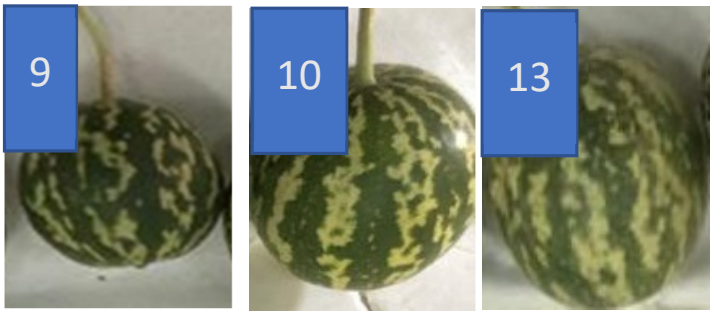


Figure 6. Variation in size and stripe patterns of *Citrullus colocynthis* fruits of the three accessions used in the present study.

Seeds of these accessions were sown in the botanical garden of the University of Sharjah in February 2021. The garden soils are sandy, similar to the soils of *C. colocynthis* in natural habitats. Plants received water as needed without adding any fertilizers. According to the nearest meteorological data in the Sharjah Airport, the climate of the botanical garden is hot and arid, with around 100 mm annual rainfall. During the study year, the seasonal temperature variation ranged from 7 to 12 °C in January and February and to 45 to 46 °C in June, July, and August. The relative humidity was also highest during the summer months (June–September) and lowest in winter (December–March) (Weather Spark, online data).

4.2. Seed Collection and Germination

Fully ripened yellow fruits were collected from 6–7 individuals of each accession in summer (August 2021) and winter (February 2022). The yellowish color of fruits was used as an indicator for fruit ripening. Seeds were extracted manually, washed in running water, air-dried, and germinated within a month after collection.

Seeds of the different accessions were germinated in two programmed incubators adjusted to a daily night/day temperature regime of 20/25 and 25/35 °C in alternating 12 h darkness/12 h light. The high temperature coincided with 12 h of white light, and the low temperature coincided with 12 h of darkness. The salinity effect was simulated using three concentrations of NaCl (0, 50, and 100 mM). In addition, the drought was simulated using different concentrations of PEG 6000 that created three different osmotic potentials (0, −0.3, −6 MPa). Germination was performed in tight-fitting 9 cm Petri dishes on a Whatman No. 1 filter paper moistened with 10 mL of the test solution. Dishes treated with the two osmotica were wrapped with parafilm sheets as an additional precaution for minimizing water evaporation. Each treatment was replicated with four Petri dishes, each with 25

seeds. All dishes were randomly organized on the different shelves of the two incubators. Seeds germinated in light were counted and removed every other day until no germination occurred in two consecutive counts after 26 days. Radicle protrusion was the criterion for seed germination.

4.3. Germination Recovery

On day 26, the seeds that failed to germinate in the NaCl and PEG solutions were thoroughly washed with running tap water and moved to new dishes on a Whatman No. 1 filter paper moistened with 10 mL of distilled water. The dishes were returned to the respective incubating chambers. The plates were checked every alternate day for germination for 14 days. A seed was considered to have germinated when the radicle had emerged.

4.4. Calculations and Data Analysis

The germination rate index (GRI) was calculated according to the modified Timson's germination velocity index: $\sum G/T$, where "G" is the percentage of seed germinated every other day, and "T" is the total germination period. The maximum possible value for our data using the GRI was 50 (1300/26). The higher the GRI, the faster the germination.

The germination recovery percentage (GR%) was calculated according to this formula:

$$GR\% = (a - b)/(c - b) \times 100,$$

where 'a' is the total number of seeds germinated after being transferred from a NaCl or PEG solution to distilled water, 'b' is the total number of seeds germinated in a NaCl or PEG solution, and 'c' is the total number of soaked seeds.

Four-way ANOVAs were used to assess the significance of the season of fruit collection, accession, the temperature of incubation, and NaCl concentration (or PEG concentration) on the final germination, GRI, and germination recovery. We assumed that all comparison groups have the same variance; all treatments have equal replicates. Treatment means were compared by Tukey's test (honestly significant differences, HSD) (p = 0.05). The GRI was log-transformed, and germination percentages were arcsine-transformed to meet the ANOVA assumptions. These transformations improved the normality of the data distribution. All statistical analyses were performed with SYSTAT version 13.0.

5. Conclusions

Germination level and tolerance to salinity and water deficit stress depend on accessions, time of fruit collection, and incubation temperatures. These factors should be considered when collecting high-quality seeds to adopt *C. colocynthis* as a cash crop in marginal habitats or to restore degraded desert habitats. Seeds with lower dormancy and higher salinity and water deficit tolerance should be collected in summer. To produce quality seeds, accessions with low seed dormancy and adapted drought and salinity stress during seed germination, such as accession 10, should be selected as maternal plants.

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