

Research Article

Study on the Differences in Salt Tolerance of *Platanus Occidentalis* Seeds Between Saline and Non-Saline Habitats

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Abstract

In this paper, we investigated the differences in salt tolerance physiological characteristics of *Platanus occidentalis* seeds from Tai'an (non-saline habitat) and Dongying (saline habitat), Shandong Province, China. Ten 18-year-old mother trees from each location were selected as sample sources. Mature fruits were collected for morphological analysis, including measurements of fruit diameter, seed length, thousand-seed weight, and water absorption swelling rate. The tested seeds were evenly placed in Petri dishes and treated with 0 (CK), 0.1%, 0.3%, and 0.5% concentration gradients of sodium chloride (NaCl) and sodium bicarbonate (NaHCO₃) solutions, respectively, followed by germination experiments under a light incubator. The results showed that seed length, thousand-seed weight, and fruit diameter of seeds from Tai'an were greater than those from Dongying. Seeds from Tai'an exhibited higher germination rate, germination potential, germination index, vigor index, and lower mean germination time, along with higher seedling fresh weight than those from Dongying under the influence of NaCl and NaHCO₃ solutions. The germination rate, germination potential, germination index, and vigor index significantly decreased, except for mean germination time, showing no significant difference; seedling fresh weight and root length also declined significantly with increasing concentrations of NaCl or NaHCO₃ solutions. However, NaHCO₃ additionally significantly inhibited root average diameter and root tip number compared with NaCl. Overall, the salt tolerance of *Platanus occidentalis* seeds from Tai'an (non-saline habitat) was significantly higher than that from Dongying (saline habitat), and the inhibitory effect of NaHCO₃ was stronger than that of NaCl.

Keywords

Platanus Occidentalis, Saline Habitat, Non-saline Habitat, Salt Stress, Seed Germination, NaCl, NaHCO₃

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Received: 22 September 2026; Accepted: 29 September 2026; Published: 20 October 2026



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1. Introduction

Soil salinization has become one of the research hotspots worldwide. According to statistics, 20% of the world's cultivated land and nearly half of the irrigated land are affected by salt stress [1], and saline-alkali land in China accounts for approximately 10% of the country's total cultivated land area [2]. The effects of saline-alkali soil on plant seed germination and growth are mainly manifested as osmotic stress, ion toxicity, and high pH stress. Salt stress is usually caused by neutral salts, with NaCl as a representative. Its main hazards are ion toxicity and osmotic imbalance. Studies have shown that low concentrations of NaCl can promote seed germination [3]. As the stress concentration increases, seed germination rate and germination potential decrease to varying degrees [4], and seedling dry mass, root length, and root surface area are reduced [5], with significant inhibitory effects on seed germination and seedling growth [6, 7]. In contrast, alkaline stress is caused by alkaline salts, mainly NaHCO_3 [8]. In addition to the effects of salt stress, it also causes direct damage induced by high pH, such as reduced cell membrane stability [9], nutrient imbalance, and metabolic disorders [10], thereby making the damaging effects of alkaline stress on plant seeds stronger [11] and exerting inhibitory and delayed effects on plant seed germination [12]. Studies have shown that with increasing mass concentration of NaHCO_3 , seed germination rate and germination potential gradually decrease, and seedlings can tolerate low mass concentrations of NaHCO_3 solution [13], while high concentrations of NaHCO_3 treatment significantly inhibit seedling height and root length [14]. Yang et al. [15] showed that the relative germination rate of *Echinochloa frumentacea* first increased and then decreased with increasing NaHCO_3 concentration. Overall, under saline-alkali stress, seed germination potential, germination rate, germination index, and seedling root length and shoot length all showed a decreasing trend [16], and the inhibitory effect intensified with increasing stress severity [17]. Moreover, the inhibitory effect of NaHCO_3 on seed germination and growth was more significant than that of NaCl [18], and the plant survival rate under NaHCO_3 stress was lower than that under NaCl stress at the same concentration [19]. Saline-alkali stress severely restricts plant growth and ecological restoration processes [20]. This makes the screening of salt-tolerant tree species a key issue in saline-alkali land management and sustainable agricultural development.

Differences in seed quality among different provenances can affect seed germination [21]. Seed size is one of the core indicators of seed quality and has an important influence on seed germination and seedling establishment [22]. Larger seeds contain more nutrients and store more energy, which can be used for early seed germination; therefore, they are generally considered beneficial to species reproduction and development [23], manifesting as higher germination capacity and

seedling survival rate [24, 25]. However, under adverse conditions, the germination capacity of seeds of different sizes is not consistent. Some studies have found that under adverse conditions, large seeds have stronger germination capacity than small seeds [26-29], and the seedling biomass germinated from large seeds is significantly higher than that from small seeds [28]. However, some studies suggest that the germination advantage of seeds of different sizes is affected by the degree of environmental stress [29, 30]. Meanwhile, other studies have found that small seeds have a greater advantage in germination under adverse conditions [31], and some studies have also pointed out that under adverse conditions, seed size has no significant effect on germination [32].

Platanus occidentalis belongs to the family *Platanaceae* and the genus *Platanus*, and is distributed in North America, Europe, and western and southeastern Asia. *Platanus* is known as the "king of street trees in the world" due to its wide distribution, rapid growth, strong adaptability, outstanding pollution resistance, and significant ecological benefits, making it one of the excellent choices for urban greening [33]. The study by Liu et al. [34] showed that because of its large canopy, dense shade, and straight trunk, the transpiration of the *Platanus* canopy can reduce the surrounding environmental temperature by up to 5.1 °C, and the vertical cooling in the human activity layer under the canopy and shade can reach 10 °C, effectively improving the local microclimate and playing a great role in mitigating the urban heat island effect. At present, *P. occidentalis* has been planted on a relatively large scale in urban greening in coastal saline-alkali land, but research on its saline-alkali tolerance is relatively limited. This study investigated the germination process and early seedling characteristics of *P. occidentalis* seeds from non-saline-alkali land and saline-alkali land under NaCl and NaHCO_3 stress, aiming to reveal the differences in seed salt tolerance among different growth environments and provide a basis for the selection of urban greening tree species in saline-alkali land.

2. Materials and Methods

2.1. Seed Collection

Seeds of *P. occidentalis* from non-saline habitat were collected in April 2024 on the east side of the road north of the intersection of Panhe Street and Wenquan Road in Tai'an, while seeds of *P. occidentalis* from saline habitat were collected in March 2024 in Hekou District, Dongying. The *P. occidentalis* trees in the Tai'an area were approximately 18 years old, with a mean diameter at breast height (DBH) of 34.1 cm and a mean tree height of 10 m, whereas those in the Dongying area were approximately 18 years old, with a mean DBH of 26 cm and a mean tree height of 9 m. Ten mother trees were randomly selected from each location, and 5-10 fruits were

collected from each mother tree. The fruits were harvested using a high-branch pruner and brought back to the laboratory.

2.2. Experimental Design

Twenty fruits were randomly selected from the fruits collected at each of the two locations, and their diameters were measured with a vernier caliper. The mature fruit balls were sealed in ziplock bags and subjected to mechanical crushing, followed by friction separation using a stainless steel sieve (with a pore size gradient of 2.0 mm). Physical separation of the fluff and needle-like seeds was achieved through sieving, and secondary separation of seed hairs was accomplished by wind. Finally, after morphological screening, 3,000 pure seed samples meeting the experimental requirements were obtained from each of the two locations. Thirty seeds were randomly selected from the seeds of each location to measure their length. Considering the time consumption of seed acquisition, the 100-seed method was adopted in this study to determine the 1000-seed weight. Additionally, 500 seeds from each location were divided into five groups and weighed. The seeds were then soaked in warm water for 24 h, removed, and blotted dry to measure their weight. The imbibition rate of seeds from the two locations was calculated using the imbibition rate formula.

In this experiment, NaCl and NaHCO₃ solutions were used to simulate salt stress and alkaline stress, respectively, with solution concentration gradients of 0 (CK), 0.1%, 0.3%, and 0.5%. According to the rules for forest tree seed testing, sterilized and oven-dried Petri dishes with a diameter of 90 mm were used, and two layers of filter paper were placed inside to prepare the germination bed. The prepared salt solutions at each concentration gradient were added to the Petri dishes to fully moisten the filter paper, and the seeds were then evenly placed on the filter paper. Before sowing, the seeds needed to be fully treated. A 3% KMnO₄ solution was prepared, and the seeds were immersed in groups for disinfection for 30 min, followed by rinsing with deionized water until colorless. Then, according to the GB 2772-1999 standard, the seeds were soaked in deionized water at 50 °C for 24 h for germination acceleration before sowing. Fifty seeds were evenly placed in each Petri dish. The seeds from each location treated with salt

solution and alkaline solution were each set as one group, with five replicates per group, and four different concentration treatments were included in each replicate, totaling 80 Petri dishes. The dishes were then placed in an illuminated incubator set at 25 °C for a total of 9 days. A quantified amount of deionized water was supplemented daily. According to the rules for forest tree seed testing, the number of germinated seeds was recorded daily, and moldy and rotten *P. occidentalis* seeds and seed coats were promptly removed. The observed indicators included germination parameters (germination potential and germination rate), and the germination index, vigor index, and mean germination time were calculated according to the formulas. The experiment was terminated 9 days after the start. In each Petri dish, seedlings with the most average growth were randomly selected to measure seedling fresh weight, root length, root surface area, root average diameter, and root tip number.

$$\text{Germination rate (GR)} = (\text{number of germinated seeds} / \text{total number of tested seeds}) \times 100\%$$

$$\text{Germination potential (GP)} = (\text{number of germinated seeds on day 4} / \text{total number of tested seeds}) \times 100\%$$

Germination index (GI) = $\sum(Gt/Dt)$, where: Gt is the number of net germination on each day; Dt is the corresponding germination day.

Vigor index (VI) = $S \times GI$, where: S is the seedling fresh weight; GI is the germination index.

Mean germination time (MGT) = $(\sum D \times n) / \sum n$, where: n is the number of normal germinated seeds on each corresponding day; D is the number of days from seed placement.

2.3. Data Processing and Analysis

Data were organized and statistically analyzed using Excel with SPSS 17.0 software. Two-factor analysis of variance (ANOVA) was performed on the germination indicators and seedling indicators. If the differences were significant, multiple comparisons were then performed using the least significant difference (LSD) method, and the level of significant difference test for analysis was $P < 0.05$.

3. Results and Analysis

3.1. Seed Characteristics of *P. Occidentalis* from Saline and Non-saline Habitat

Table 1. Seed characteristics of *P. occidentalis* under different habitats.

Habitat	Fruit diameter/cm	Seed length/cm	Thousand-seed weight/g	Imbibition rate (%)
Saline habitat	3.17±0.45 a	1.17±0.11 a	3.33±0.07 a	87.60±4.72 a

Habitat	Fruit diameter/cm	Seed length/cm	Thousand-seed weight/g	Imbibition rate (%)
Non-saline habitat	3.87±0.27 b	1.23±0.08 b	4.47±0.12 b	85.60±1.34 a

Note: Different lowercase letters in the same column indicate significant differences ($P < 0.05$).

Habitat had highly significant effects on fruit diameter and seed length, significant effects on 1000-seed weight, but no significant effects on imbibition rate. The fruit diameter, seed length, and 1000-seed weight of *P. occidentalis* from non-saline habitat were all higher than those from saline habitat (Table 1). These differences in the indicators further indicate that salt stress in saline habitat inhibited the normal development of seeds, resulting in reduced morphological size, which decreased the organic substances stored in the seeds and may affect the energy supply during early germination.

3.2. Effects of Habitat and NaCl Stress on Seed Germination and Seedling Growth of *P. Occidentalis*

3.2.1. Seed Germination

Habitat had highly significant effects on the germination rate, germination potential, germination index, vigor index, and mean germination time of *P. occidentalis* seeds (Table 2). Under NaCl stress, the germination rate, germination potential, germination index, and vigor index of seeds from Tai'an were all significantly higher than those from Dongying, while the mean germination time was significantly lower than that of seeds from Dongying (Figure 1).

NaCl concentration significantly affected germination potential and had highly significant effects on germination rate,

germination index, and vigor index, but had no significant effect on mean germination time (Table 2). With increasing NaCl concentration, seed germination rate, germination potential, germination index, and vigor index all gradually decreased (Figure 1). Among the different NaCl concentrations, the difference in germination rate between CK and 0.1 was not significant ($P > 0.05$), but both were significantly higher than those at 0.3 and 0.5 ($P < 0.05$), while the difference between 0.3 and 0.5 was not significant ($P > 0.05$); the differences in germination potential among CK, 0.1, and 0.3 were not significant ($P > 0.05$), while CK and 0.1 were significantly higher than 0.5 ($P < 0.05$), and the difference between 0.3 and 0.5 was not significant ($P > 0.05$); the difference in germination index between CK and 0.1 was not significant ($P > 0.05$), but both were significantly higher than that at 0.3 ($P < 0.05$), with 0.5 being the lowest ($P < 0.05$); the difference in vigor index between CK and 0.1 was not significant ($P > 0.05$), but both were significantly higher than those at 0.3 and 0.5 ($P < 0.05$), and the difference between 0.3 and 0.5 was not significant ($P > 0.05$).

The interaction between habitat and NaCl concentration had highly significant effects on germination rate, germination index, and vigor index, but had no significant effects on germination potential or mean germination time (Table 2). With increasing NaCl concentration, the seeds from the Tai'an area showed a trend of first increasing and then decreasing in these three indicators, whereas those from the Dongying area decreased gradually (Figure 1).

Table 2. Two-way ANOVA of seed germination and seedling traits of *P. occidentalis* from different habitats under different NaCl concentrations.

Parameter	Habitat		NaCl concentration		Habitat×NaCl concentration	
	F-value	P-value	F-value	P-value	F-value	P-value
Germination rate	620.298	<0.001	7.307	0.002	15.613	<0.001
Germination energy	318.196	<0.001	3.626	0.034	2.833	0.069
Germination index	545.909	<0.001	11.063	<0.001	6.617	0.004
Vigor index	133.396	<0.001	12.111	<0.001	10.062	<0.001
Mean germination time	64.486	<0.001	3.972	0.26	1.779	0.189
Seedling fresh weight	1153.943	<0.01	17.731	<0.01	12.678	<0.01
Root tip number	0.471	0.502	1.861	0.174	0.161	0.921
Root length	4.464	0.050	11.992	<0.001	2.118	0.136
Root average diameter	1.381	0.256	1.444	0.256	2.484	0.096

Parameter	Habitat		NaCl concentration		Habitat×NaCl concentration	
	F-value	P-value	F-value	P-value	F-value	P-value
Root surface area	3.697	0.071	3.789	0.03	1.286	0.311

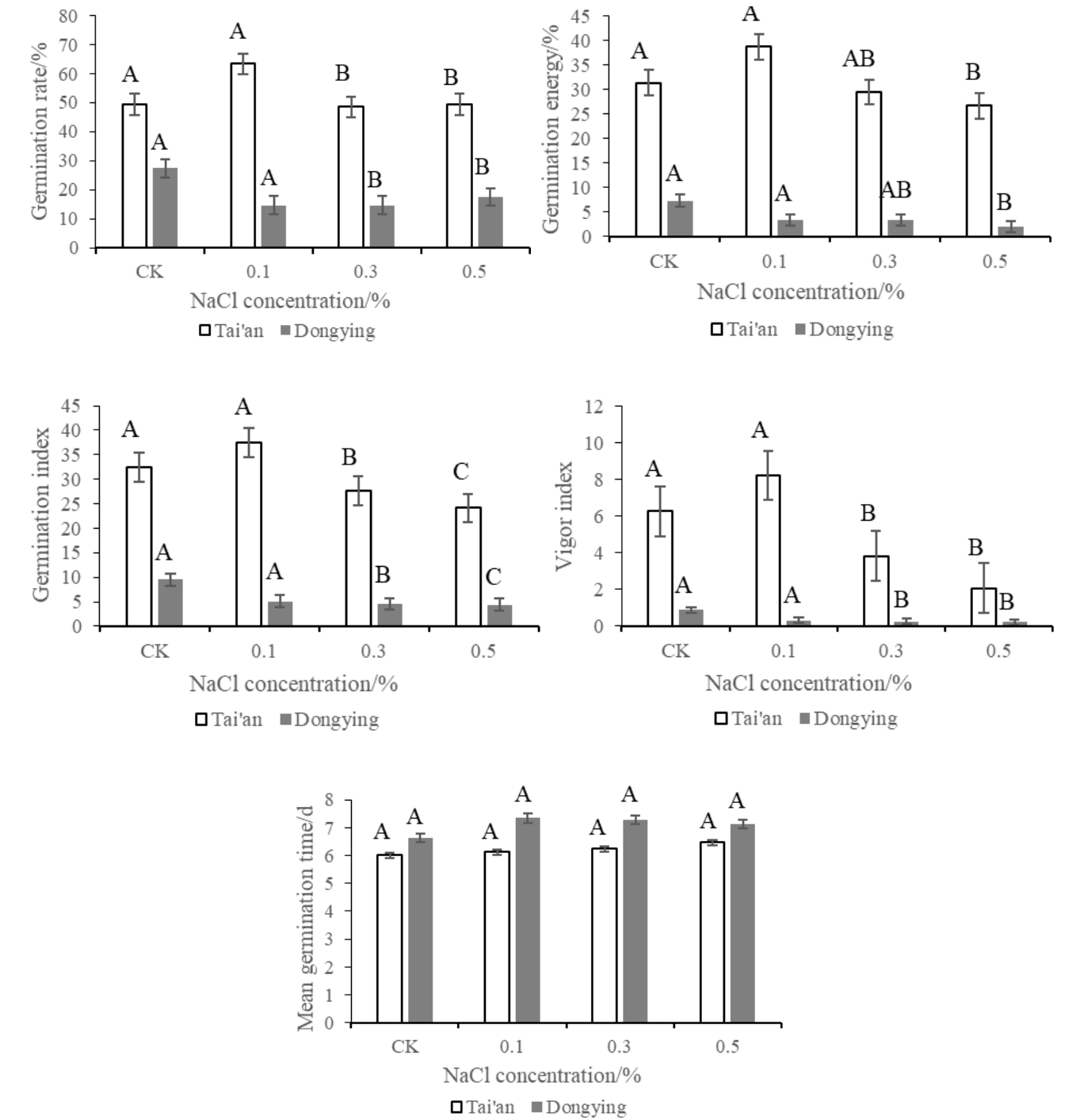


Figure 1. Effects of different NaCl concentrations on seed germination of *P. occidentalis* from different habitats.

Different uppercase letters indicate significant differences among treatments within the same habitat ($P < 0.05$). The same applies below.

3.2.2. Seedling Growth

As shown in Table 2, habitat had highly significant effects on seedling fresh weight, but had no significant effects on root length, root average diameter, root surface area, or root tip number. NaCl concentration had highly significant effects on seedling fresh weight and root length, significant effects on root surface area, but no significant effects on root average diameter or root tip number. The interaction between habitat and NaCl stress had highly significant effects on seedling fresh weight, but had no significant effects on root length, root surface area, root average diameter, or root tip number.

As shown in Figure 2, compared with the Dongying area, seedlings developed from seeds from the Tai'an area had higher seedling fresh weight. The general trends of changes in

fresh weight, root length, and root surface area of *P. occidentalis* seedlings from the Tai'an area all decreased with increasing salt concentration. Among the different NaCl concentrations, the difference in root length between CK and 0.1 was not significant ($P > 0.05$), while CK was significantly greater than 0.3 ($P < 0.05$); the difference between 0.1 and 0.3 was not significant ($P > 0.05$), and 0.5 was the lowest ($P < 0.05$). The root surface area was the largest in the CK group ($P < 0.05$), and the differences among 0.1, 0.3, and 0.5 were not significant ($P > 0.05$). The difference in seedling fresh weight between CK and 0.1 was not significant ($P > 0.05$), but both were significantly greater than that at 0.3 ($P < 0.05$), with 0.5 being the lowest ($P < 0.05$). With increasing NaCl concentration, the difference in seedling fresh weight between the Tai'an and Dongying areas gradually decreased.

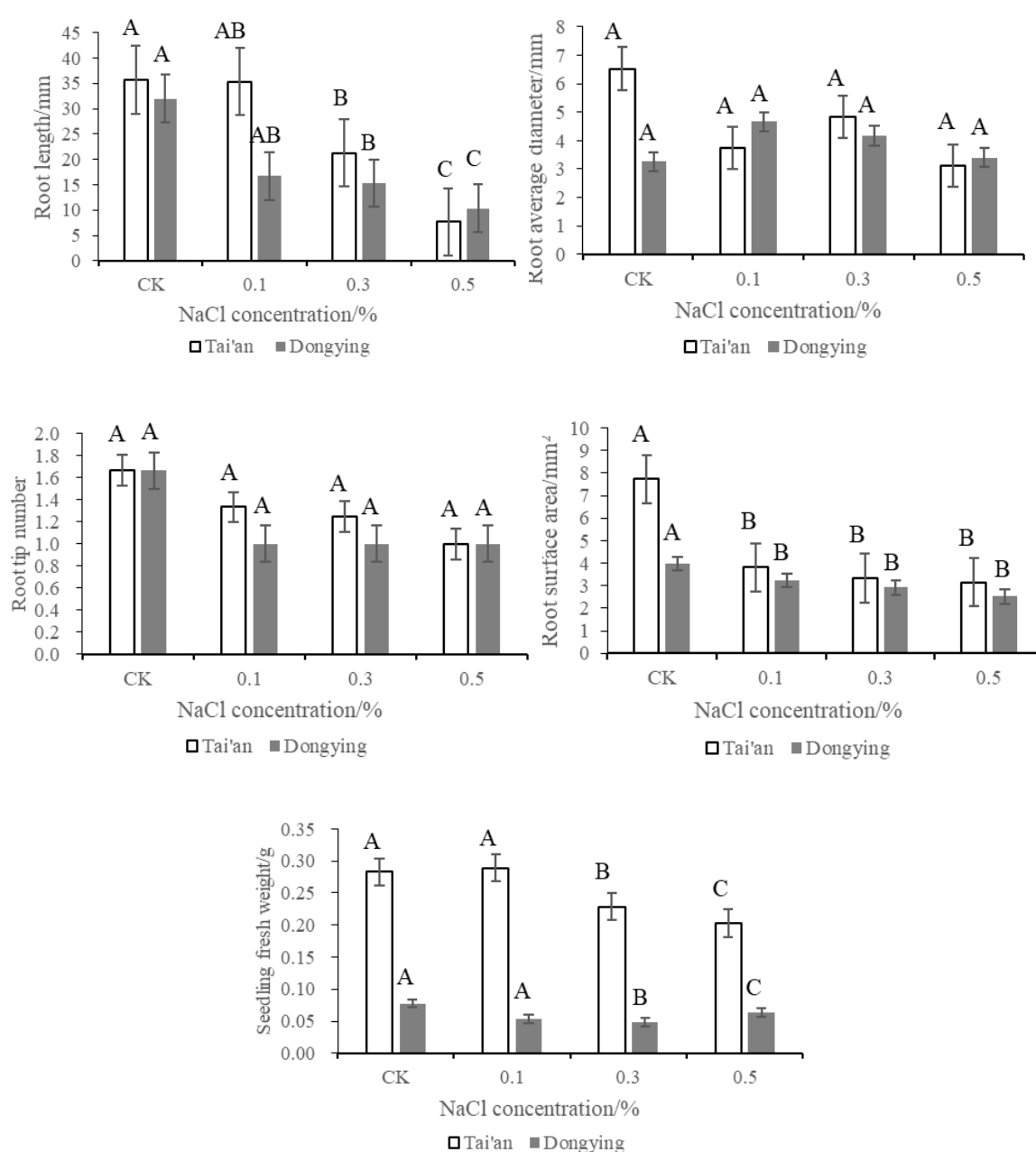


Figure 2. Effects of different NaCl concentrations on seedling growth of *P. occidentalis* from different habitats.

3.3. Effects of Habitat and NaHCO₃ Stress on Seed Germination and Seedling Growth of *P. Occidentalis*

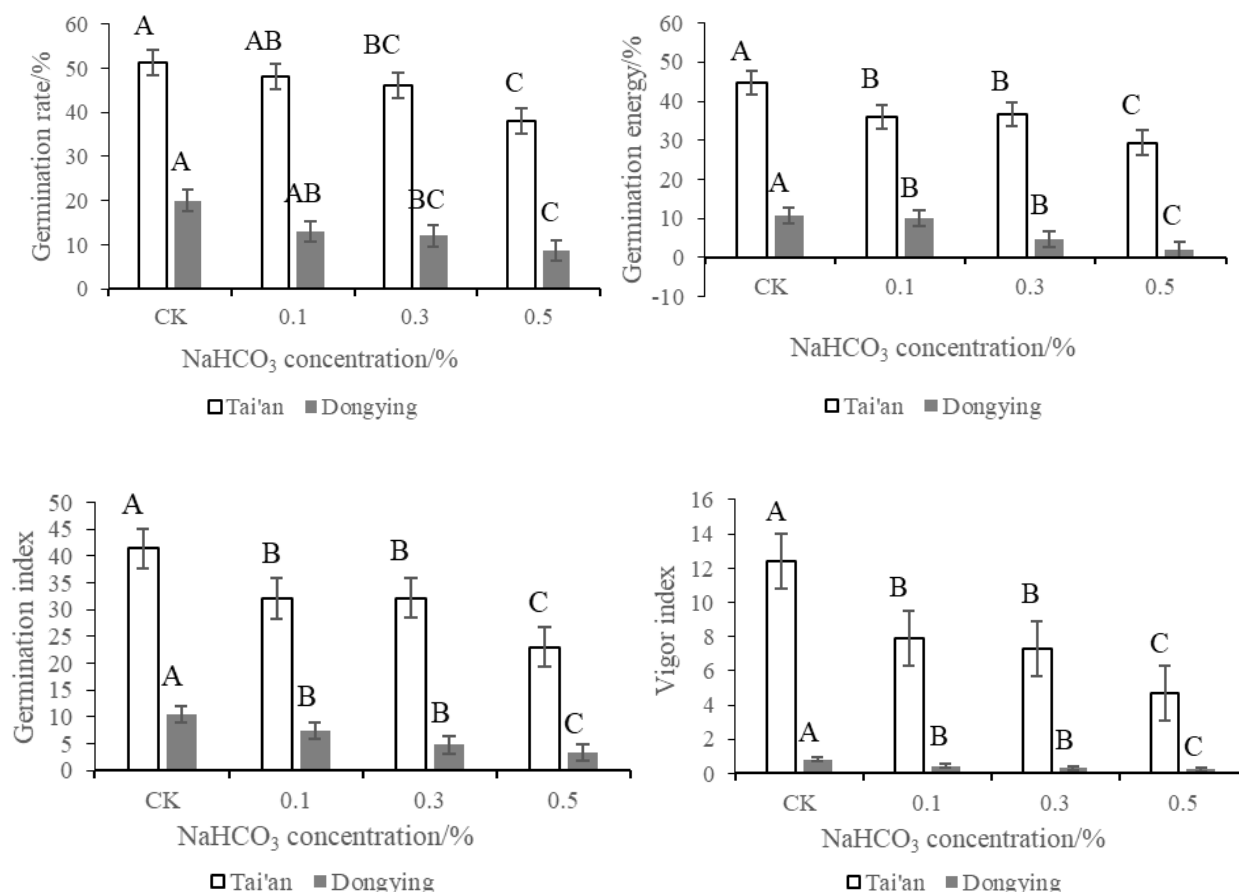
3.3.1. Seed Germination

Habitat had highly significant effects on the germination rate, germination potential, germination index, vigor index, and mean germination time of *P. occidentalis* seeds (Table 3). The germination rate, germination potential, germination index, and vigor index of seeds from Tai'an were all significantly higher than those of seeds from Dongying, while the mean germination time of seeds from Tai'an was significantly lower than that of seeds from Dongying (Figure 3).

NaHCO₃ concentration had highly significant effects on germination rate, germination potential, germination index, and vigor index, but had no significant effect on mean germination time (Table 3). With increasing NaHCO₃ concentration, the values of germination rate, germination potential, germination index, and vigor index all gradually decreased (Figure

3). Among the different NaHCO₃ concentrations, the difference in germination rate between CK and 0.1 was not significant ($P > 0.05$), while CK was significantly greater than 0.3 ($P < 0.05$); the difference between 0.1 and 0.3 was not significant ($P > 0.05$); CK and 0.1 were significantly greater than 0.5 ($P < 0.05$), and the difference between 0.3 and 0.5 was not significant ($P > 0.05$). For germination potential, germination index, and vigor index, CK was significantly greater than 0.1 and 0.3 ($P < 0.05$), with no significant difference between 0.1 and 0.3 ($P > 0.05$), and 0.5 was the lowest ($P < 0.05$).

The interaction between habitat and NaHCO₃ concentration had highly significant effects on germination index and vigor index, but had no significant effects on germination rate, germination potential, or mean germination time (Table 3). Overall, with increasing NaHCO₃ concentration, the differences in germination index and vigor index between seeds from the Tai'an area and those from the Dongying area gradually decreased (Figure 3).



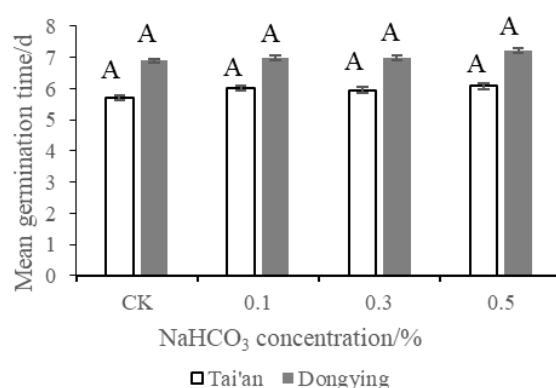


Figure 3. Effects of different NaHCO₃ concentrations on seed germination of *P. occidentalis* from different habitats.

Table 3. Two-way ANOVA of seed germination and seedling traits of *P. occidentalis* from different habitats under different NaHCO₃ concentrations.

Parameter	Habitat		NaHCO ₃ concentration		Habitat×NaHCO ₃ concentration	
	F-value	P-value	F-value	P-value	F-value	P-value
Germination rate	289.175	<0.001	7.942	0.002	0.450	0.721
Germination energy	530.229	<0.001	16.573	<0.001	2.103	0.146
Germination index	879.423	<0.001	40.784	<0.001	8.546	0.002
Vigor index	703.353	<0.001	41.094	<0.001	29.801	<0.001
Mean germination time	49.709	<0.001	1.011	0.417	0.097	0.96
Seedling fresh weight	96.218	<0.001	20.664	<0.001	1.723	0.208
Root tip number	0.636	0.438	4.532	0.02	0.521	0.675
Root length	3.931	0.067	23.804	<0.001	1.473	0.265
Root average diameter	9.551	0.008	13.988	<0.001	3.6	0.041
Root surface area	14.342	0.002	3.058	0.063	7.195	0.004

3.3.2. Seedling Growth

As shown in Table 3, habitat had highly significant effects on seedling fresh weight, root average diameter, and root surface area, but had no significant effects on root tip number or root length. NaHCO₃ stress had highly significant effects on seedling fresh weight, root length, and root average diameter, significantly affected root tip number, but had no significant effect on root surface area. The interaction between habitat and NaHCO₃ concentration had highly significant effects on root surface area and significant effects on root average diameter, but had no significant effects on seedling fresh weight, root tip number, or root length.

As shown in Figure 4, compared with those from the Dongying area, seedlings developed from seeds from the Tai'an area had higher seedling fresh weight and root surface area. With increasing NaHCO₃ concentration, seedling fresh

weight, root length, root average diameter, and root tip number all gradually decreased. Among the different NaHCO₃ concentrations, the difference in root average diameter between CK and 0.1 was not significant ($P > 0.05$), while both were significantly greater than those at 0.3 and 0.5 ($P < 0.05$), and the difference between 0.3 and 0.5 was not significant ($P > 0.05$); the difference in root tip number between CK and 0.1 was not significant ($P > 0.05$), while CK was significantly greater than 0.3 and 0.5 ($P < 0.05$), and the differences among 0.1, 0.3, and 0.5 were not significant ($P > 0.05$); seedling fresh weight in the CK group was significantly greater than that at 0.1 and 0.3 ($P < 0.05$), the difference in seedling fresh weight between 0.1 and 0.3 was not significant ($P > 0.05$), and 0.5 was the lowest ($P < 0.05$); for root length, $CK > 0.1 > 0.3 > 0.5$ ($P < 0.05$). The differences in root surface area and root average diameter between the Tai'an and Dongying areas became smaller with increasing NaHCO₃ concentration.

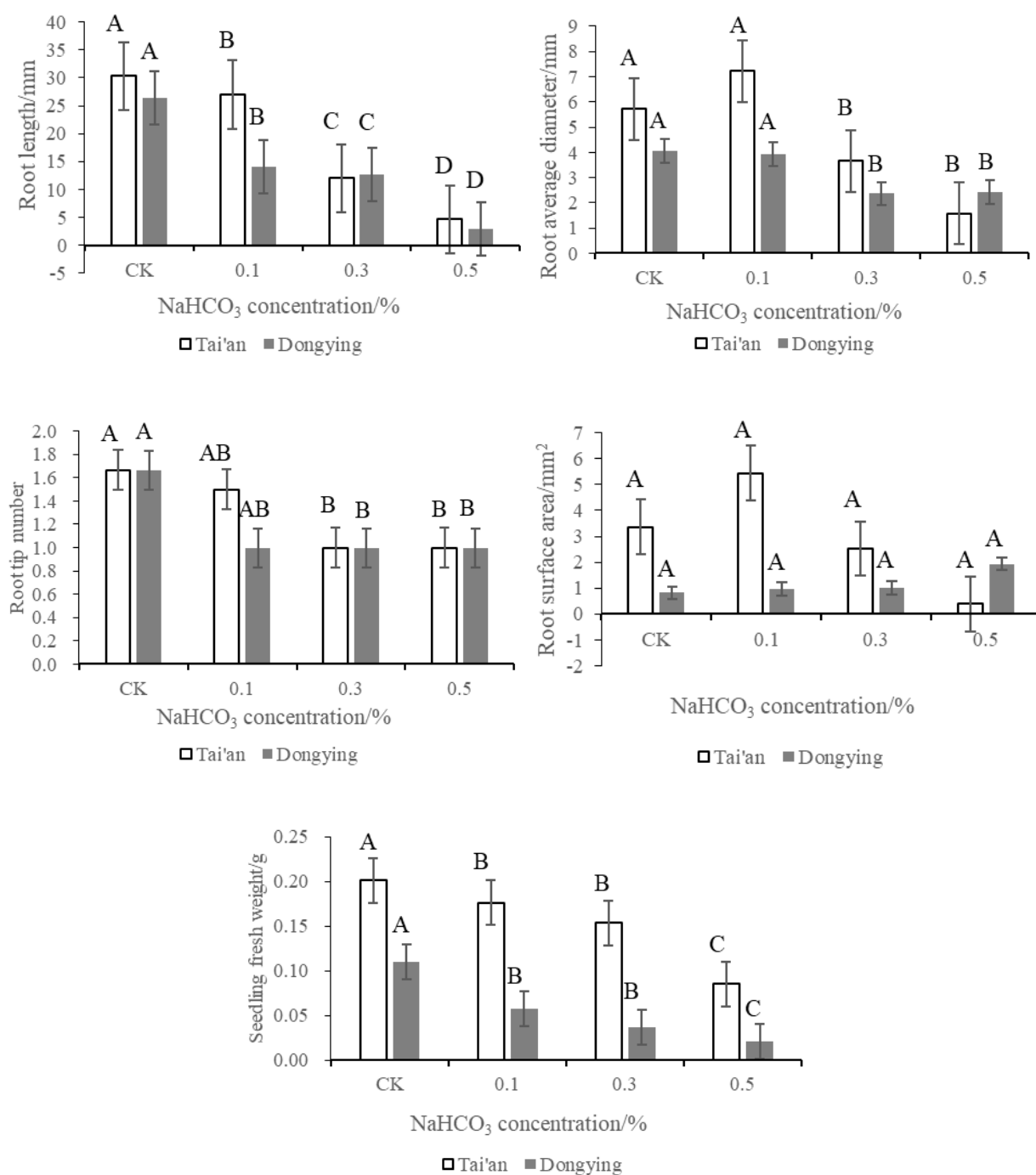


Figure 4. Effects of different NaHCO₃ concentrations on seedling growth of *P. occidentalis* from different habitats.

4. Discussion

4.1. Effects of Salt Stress on Seed Germination and Seedling Growth

The seed germination stage and seedling stage are the periods most sensitive to environmental stress in the plant life cycle [35]. In this study, NaCl stress significantly inhibited the

seed germination and early seedling growth of *P. occidentalis*. During the germination stage, an increase in NaCl concentration significantly reduced the germination rate and germination potential of seeds, and highly significantly impaired the overall speed and vigor performance of seed germination. Meanwhile, NaCl stress generally prolonged the time required for seeds to progress from water imbibition to germination, slowing down the germination process, which is consistent with the findings of Tong et al. [36] and Xu et al. [37]. During the seedling growth stage, the negative effects of NaCl stress

were equally significant: first, it highly significantly inhibited the accumulation of seedling biomass [38], reducing fresh weight; at the same time, the root elongation capacity of seedlings was highly significantly inhibited [39], and the total area of root-soil contact was also significantly reduced, which greatly limited the ability of seedlings to absorb water and nutrients. Studies have shown that when plants are subjected to NaCl stress, the root system immediately perceives changes in the external environment [40], thereby slowing down the transport of water and nutrients, and consequently inhibiting biomass accumulation [41]. Lin et al. [42] showed that with increasing degrees of NaCl stress, the germination rate, germination index, and vigor index of *Robinia pseudoacacia* seeds were significantly reduced, while the mean germination time was significantly increased; seedling water content, biomass, root length, root surface area, specific root length, and specific root surface area were significantly reduced, and NaCl stress significantly inhibited seed germination, seedling growth, and root development of *Robinia pseudoacacia*. Taken together, NaCl salt stress, mainly through the dual effects of osmotic stress and ion toxicity, significantly inhibits seed germination and vigor, and severely suppresses early seedling biomass accumulation and root development, thus becoming a key limiting factor for its propagation, cultivation, and natural survival in saline-alkali soils.

This study found that NaHCO₃ stress significantly inhibited the seed germination and seedling growth of *P. occidentalis*. During the seed germination stage, NaHCO₃ stress exerted highly significant inhibitory effects on the germination rate, germination potential, germination index, and vigor index, while its effect on the mean germination time was not significant. Qiao's [13] study on naked oats also showed that the seed germination rate gradually decreased with increasing NaHCO₃ concentration. In this study, during the seedling stage of *P. occidentalis*, the inhibition was manifested in multiple dimensions: fresh weight, root length, and average root diameter were highly significantly reduced, and the number of root tips was significantly decreased, but the change in root surface area was not significant. Pei et al. [43] also found that the seedling fresh weight and radicle length of buckwheat decreased with increasing NaHCO₃ solution concentration. Cai et al.'s [44] study on rapeseed found that the root length of Huayouza 62 first increased and then decreased with increasing NaHCO₃ concentration, whereas the root length of Xiangyou 15 gradually decreased with increasing NaHCO₃ concentration. Under NaHCO₃ stress, osmotic stress and ion toxicity act synergistically, jointly reducing germination potential, hindering biomass accumulation, and impairing root development, ultimately restricting the growth of *P. occidentalis* in saline-alkali environments.

By comparing the data from the two treatments, it can be seen that both NaCl and NaHCO₃ stress had substantial effects on the seeds of *P. occidentalis*. Both hindered seed germination and seedling growth through the dual effects of osmotic stress and ion toxicity, exerting varying degrees of influence

on each index, with the effects being particularly pronounced under high-concentration stress. However, the two treatments also affected different indices of seed germination and seedling growth of *P. occidentalis* to varying degrees. During the seed germination stage, NaHCO₃ had highly significant effects on the germination rate, germination potential, germination index, and vigor index of *P. occidentalis* seeds, whereas NaCl had highly significant effects only on the germination index and vigor index, and significant effects on the germination rate and germination potential, indicating that the inhibitory effect of NaHCO₃ on seed germination was greater than that of NaCl. This is consistent with the findings of Wang et al. [45], Pan et al. [46], and Lei et al. [47], who reported that plant materials are more sensitive to NaHCO₃ alkaline stress than to NaCl salt stress at corresponding concentrations. This may be because, in addition to the effects of Na⁺ ion toxicity and osmotic stress on the seed germination of *P. occidentalis*, the high pH stress induced by alkaline salts [7] causes cell membrane damage [48], reduces plant root activity and nutrient uptake rates [49], and decreases the availability of mineral elements [19], thereby causing further inhibition and damage to seed germination [50]. During the seedling growth stage, both treatments had highly significant effects on seedling fresh weight and root length, indicating that both greatly affected seedling biomass accumulation and root elongation capacity. The difference is that NaHCO₃ also had significant effects on the average root diameter and number of root tips of seedlings, whereas NaCl did not significantly affect these two parameters but did significantly affect root surface area, suggesting that the two treatments have different modes of influence on root growth.

4.2. Effects of Habitat on Seed Germination and Seedling Growth

A large number of studies have shown that seed size determines seed quality and is related to the nutrients contained in seeds [51, 52]. In this study, the fruit diameter, seed length, and thousand-grain weight of *P. occidentalis* from non-saline habitat were all significantly higher than those from saline habitat. Under salt stress conditions, the germination rate, germination potential, germination index, vigor index, and seedling fresh weight of seeds from non-saline habitat in Tai'an were all significantly higher than those of seeds from saline habitat in Dongying, and seeds from saline habitat had a longer mean germination time than those from non-saline habitat. This is consistent with the findings of Wu et al. [53], in which the germination rate, germination potential, germination index, and vigor index of *Fraxinus velutina* seeds from non-saline habitat were significantly higher than those of seeds from saline habitat. A significant advantage of large seeds in seedling biomass has also been found in *Pinus thunbergii* [24] and *Quercus acutissima* [25]. Large seeds are rich in nutrients [54] and have higher germination rates, growth

rates, and survival competitiveness [25]; under adverse conditions, large seeds have stronger resistance and adaptability than small seeds. Studies have shown that the vigor index of mulberry seeds from non-saline habitat is higher than that of seeds from saline habitat, which is closely related to their higher thousand-grain weight compared with seeds from saline habitat [55]. When plants grow in saline habitat for a long time, maintaining their salt tolerance and continued growth in a saline medium requires the consumption of large amounts of nutrients for physiological regulation and adaptation to the saline-alkali environment, thereby limiting their growth and reducing nutrient allocation to seeds [56]. Since the early growth of seedlings mainly depends on the nutrient substances contained in the seeds [24], the fresh weight of seedlings from saline habitat is smaller than that of seedlings from non-saline habitat. The strong salt tolerance of seeds from non-saline habitat is related to the fact that their growth is not affected by salt stress. However, Liu et al. [56] showed that seeds of *Ulmus pumila* from saline habitat had a higher germination index and a lower mean germination time than those from non-saline habitat, which is inconsistent with the results of this study. This may be related to the strong salt tolerance of *Ulmus pumila*, which, after many years of reproduction and natural selection, has adapted to the saline-alkali environment and developed genetic variation with a certain degree of salt tolerance.

5. Conclusion

This study found that seeds from non-saline habitat in Tai'an had a higher thousand-grain weight, as well as higher germination capacity and early seedling biomass, than seeds from saline habitat in Dongying. This indicates that the seed quality from non-saline habitat is superior to that from saline habitat, and the seeds also possess stronger salt tolerance. Both NaCl and NaHCO₃ stress significantly inhibited the seed germination and early seedling growth of *P. occidentalis*, and the effects decreased significantly with increasing salt concentration, and the inhibitory effects intensified with increasing concentration, indicating that this tree species is sensitive to salt stress. Overall, NaHCO₃ exhibited a stronger inhibitory effect on the seed germination of *P. occidentalis* than NaCl.

Abbreviations

GR	Germination Rate
GP	Germination Potential
GI	Germination Index
VI	Vigor Index
MGT	Mean Germination Time
ANOVA	Analysis of Variance
LSD	Least Significant Difference

Author Contributions

Lin Qi: Writing – original draft

Yong Zhao: Writing –original draft

Ziliang Zhang: Methodology

Haiyan Liu: Formal Analysis

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Yang G, Tang L, Li S, Zhao C. Study on the difference of seed germination and salt tolerance of four *Brassica napus* varieties in Xizang. Seed, 2024, 43(2): 104-110. <https://doi.org/10.16590/j.cnki.1001-4705.2024.02.104>
- [2] Hu H, Cui L, Wang J, Wang Z, Du J. Salt tolerance of seeds of different *Elymus sibiricus* lines at germination stage. Journal of Arid Land Resources and Environment, 2022, 36(11): 119-126. <https://doi.org/10.13448/j.cnki.jalre.2022.284>
- [3] Liu Z, Liu C, Zheng K, Zhuang J. Effects of different sodium salt stress on seed germination and seedling growth of *Robinia pseudoacacia*. Seed, 2022, 41(10): 65-72. <https://doi.org/10.16590/j.cnki.1001-4705.2022.10.065>
- [4] Lian J, Ao Y, Lu T, Yan B. The effects of salt stress on four *Xanthoceras sorbifolium* provenances and their salt tolerance comprehensive evaluation. Journal of Northeast Forestry University, 2024, 52(6): 20-26.
- [5] Huang H, Fu J, Cao B, Zhao W, Hao M, Mao P, Wang T, Hao Y, Zhang X, Tan H. Effects of salt stress and temperature on seed germination and seedling growth of *Morus alba*. Journal of Southwest Forestry University (Natural Sciences Edition), 2021, 41(2): 30-37. <https://doi.org/10.12153/j.issn.1674-991X.20230061>
- [6] Jia F, Li L, Tan L, Chen Y, Song X, Li J, Liang M. Responses of seed germination and seedling growth of *Celosia argentea* to various stresses. Journal of Southwest Forestry University (Natural Sciences Edition), 2025, 45(4): 11-17. <https://doi.org/10.15302/J-SSCAE-2023.07.028>
- [7] Yu Z, Yan H, Zhang H, Yang X. Effect of different salt stresses on seed germination and seedling physiological characteristics of *Gleditsia sinensis*. Journal of Northeast Agricultural University, 2020, 51(10): 28-35.
- [8] Zheng X, Li A, Wu C, Nie R, Ji X, Wang R, Dong M, Zhang J. Physiological responses of red kernel walnut seedlings to saline-alkali compound stress. Journal of Nanjing Forestry University (Natural Sciences Edition), 2026, 50(3): 14-26.
- [9] Wang T, Zhang Z, Liu M, Wang Y, An C, Gong L. Differential effects of saline and alkaline stress on water uptake and germination of alfalfa seeds. Pratacultural Science, 2025, 42(12): 3108-3119. <https://doi.org/10.11829/j.issn.1001-0629.2024-0578>

- [10] Zhao W, Li A, Zhu Y, Li Y, Ye Z, Ren H. Effects of γ -aminobutyric acid and chlorinated hemin composite coating on seed germination and seedling growth of *Psathyrostachys juncea* under drought and salt stresses. *Chinese Journal of Applied Ecology*, 2026, 37(1): 82-92.
<https://doi.org/10.13287/j.1001-9332.202601.011>
- [11] Zhang T, Sheng J, Wang R, Li H, Yang Y. Effects of salt-alkali stress and temperature on seed germination of *Artemisia scoparia*. *Acta Agrestia Sinica*, 2019, 27(3): 581-588.
<https://doi.org/10.11733/j.issn.1007-0435.2019.03.009>
- [12] Qi W, Li Y, Ma H, Wu H. Intraspecific variation of seed germination characteristics of *Leymus chinensis* under salt stress and its influencing factors. *Acta Ecologica Sinica*, 2025, 45(11): 5481-5496. <https://doi.org/10.20103/j.stxb.202410292630>
- [13] Qiao F. Effects of osmoregulation substances and antioxidant enzyme activities of *Avena nuda* L. seedlings treated with NaHCO_3 . *Journal of Gansu Agricultural University*, 2022, 57(5): 53-60. <https://doi.org/10.13432/j.cnki.jgsau.2022.05.007>
- [14] Meng C, Lu X, Wang J, Wei Y, Zhang C, Li Y, Xu Z. Effects of different salt stresses on triticale seed germination. *Acta Prataculturae Sinica*, 2023, 32(12): 171-180.
<https://doi.org/10.11686/cyxb2023068>
- [15] Yang Y, Mao G, Ma D, Zhang F, Xu X. Germination characteristics of four forage seeds under different concentrations of NaCl or NaHCO_3 stress. *Acta Agrestia Sinica*, 2022, 30(3): 637-645.
<https://doi.org/10.11733/j.issn.1007-0435.2022.03.016>
- [16] Ji X, Peng M, Lei C, Jiang L. Effects of different types of salinity on seed germination and young seedling growth of *Halostachys capsica*. *Journal of Northwest Forestry University*, 2022, 37(3): 114-119.
<https://doi.org/10.3969/j.issn.1001-7461.2022.03.16>
- [17] Yang X, Zhang Y, Zhang S, Zhang W. Effects of salt and alkali stress on seed germination and physiological characteristics of wheat germplasm materials. *Chinese Journal of Ecology*, 2026, 45(5): 1533-1543.
<https://doi.org/10.13292/j.1000-4890.202604.015>
- [18] Zhang Y, Wang J, Wu W, Liu G, Gao Q, Yang Y, Jia S. Effects of saline-alkali stress on the seed germination and physiological characteristics of corn poppy seedlings. *Pratacultural Science*, 2025, 42(9): 2262-2274.
<https://doi.org/10.11829/j.issn.1001-0629.2024-0360>
- [19] Guo W, Wang G, Gou Q. Effects of sodium salt stress on the growth and biomass allocation of *Chenopodiaceae* annuals. *Acta Ecologica Sinica*, 2021, 41(16): 6633-6643.
<https://doi.org/10.5846/stxb202008142125>
- [20] Zhu J, Cui Z, Wu C, Deng C, Chen J, Zhang H. Research advances and prospect of saline and alkali land greening in China. *World Forestry Research*, 2018, 31(4): 70-75.
<https://doi.org/10.13348/j.cnki.sjlyj.2018.0034.y>
- [21] Yuan Q, Bai Z, Yao F, Li Q, Wang Z, Yao G, Li G. Effects of fertilization dosage on seedling quality of different provenances *Quercus variabilis*. *Journal of Southwest Forestry University (Natural Sciences Edition)*, 2023, 43(2): 17-25.
<https://doi.org/10.7606/j.issn.1004-1389.2020.09.015>
- [22] Zhang N, Wu Y, Wu Z. Study on seed characteristics and germination of *Indigofera stachyodes* from different provenances. *Seed*, 2022, 41(1): 7-13, 43.
<https://doi.org/10.16590/j.cnki.1001-4705.2022.01.007>
- [23] Li S, Zou N, Zhang D, Yuan S, Li Z, Gan Y, Zeng Y, Wu Z. Study on seed germination and seedling growth characteristics of *Rhodoleia championii* from different provenances. *Journal of Southwest Forestry University (Natural Sciences Edition)*, 2024, 44(6): 29-36.
<https://doi.org/10.11929/j.swfu.202312035>
- [24] Mao P, Guo L, Gao Y, Qi L, Cao B. Effects of seed size and sand burial on germination and early growth of seedlings for coastal *Pinus thunbergii* Parl. in the northern Shandong Peninsula, China [J]. *Forests*, 2019, 10(3): 281.
<https://doi.org/10.3390/f10030281>
- [25] Mao P, Kan X, Pang Y, Ni R, Cao B, Wang K, Zhang J, Tan C, Geng Y, Cao X, Wang S, Gao P, Dong J. Effects of forest gap and seed size on germination and early seedling growth in *Quercus acutissima* plantation in Mount Tai, China [J]. *Forests*, 2022, 13(7): 1025.
<https://doi.org/10.3969/j.issn.1000-2006.2014.05.021>
- [26] Guo Y, Liu H, Yu H, Zhao J, Hao Y. Effects of seed size and drought stress on growth of *Xanthoceras sorbifolia* seedlings. *Journal of Northwest A&F University (Natural Sciences Edition)*, 2016, 44(8): 143-147.
<https://doi.org/10.13207/j.cnki.juwafu.2016.08.021>
- [27] Fu J, Zhang C, Wang X, Liu Z, Qin Y, Zhang M, Zhao J, Zhao S, Cao B, Mao P. Effects of water stress and seed size on seed germination of *Platycladus orientalis*. *Seed*, 2020, 39(2): 50-57. <https://doi.org/10.7525/j.issn.1673-5102.2012.06.0>
- [28] Zhu S, Wang F, Liu Y, Sun T, Chai C, Zhang J, Zhang H. Effects of soil moisture and seed size on the germination, sprouting and sapling growth of *Haloxylon ammodendron*. *Journal of Northwest Forestry University*, 2021, 36(6): 16-21.
<https://doi.org/10.3969/j.issn.1001-7461.2021.06.03>
- [29] Zhao L, Mo B, Wang P, Zhang Y, Long Z. Relationship of *Sophora davidii* seed size to germination, dormancy, and mortality under water stress [J]. *South African Journal of Botany*, 2015, 99: 12-16.
- [30] Wang H, Wang P, Zhao G, Sun Q, Long Z, Zhang Y. Seed size and germination strategy of *Sophora davidii* under drought stress. *Acta Ecologica Sinica*, 2016, 36(2): 335-341.
<https://doi.org/10.1007/s11676-015-0186-x>
- [31] Ameixa O, Marques B, Fernandes V, Soares A, Calado R, Lilieb A. Dimorphic seeds of *Salicornia ramosissima* display contrasting germination responses under different salinities [J]. *Ecological engineering: The Journal of Ecotechnology*, 2016, 87: 120-123.
<https://doi.org/10.1016/j.ecoleng.2015.11.019>
- [32] Pang H, Wang J, Ao Y, Mu C. Effects of seed size and bract of *Ceratoides arborescens* on germination and seedling growth under drought stress. *Chinese Journal of Applied Ecology*, 2021, 32(2): 399-405.
<https://doi.org/10.13287/j.1001-9332.202102.001>

- [33] Wang H, Hu Y, Yan H, Wu R, Bao Z. The effect of the tree structure of *Platanus* on the microclimate and pedestrian thermal comfort in urban street. *Chinese Landscape Architecture*, 2025, 41(4): 123-129. <https://doi.org/10.19775/j.cla.2025.04.0123>
- [34] Liu B, Peng X. Measurement and analysis of vertical cooling effect on *Platanus acerifolia* street tree in summer. *Journal of Chinese Urban Forestry*, 2018, 16(5): 11-16. <https://doi.org/10.3969/j.issn.1672-4925.2018.05.003>
- [35] Wang H, Sun Y, Li S, Jia S, Yang K, Wei K, Ma C, Wang X. Effects of saline-alkali stress on seed germination, seedling growth and physiological characteristics of *Cyperus esculentus*. *Acta Agrestia Sinica*, 2026, 34(7): 2540-2552. <https://doi.org/10.11733/j.issn.1007-0435.2026.07.018>
- [36] Tong Y, Guo S, Wang X, Ma Y, Yang J, Yu D, Li S. Effects of exogenous nicotinamide supplementation on alfalfa seed germination and seedling saline-alkali tolerance. *Acta Ecologica Sinica*, 2026, 46(15): 1-18. <https://doi.org/10.20103/j.stxb.202510232758>
- [37] Xu R, Gao J, Ren B, Guan S, Ge T, Wang N. Effects of temperature on seed germination and seedling growth of two *Astragalus* species under drought and salt stresses. *Chinese Journal of Ecology*, 2020, 39(9): 2930-2934. <https://doi.org/10.13292/j.1000-4890.202009.034>
- [38] Qi L, Guo L, Liu Y, Cao B, Mao P, Li Z. Dynamic responses of non-structural carbohydrates in *Robinia pseudoacacia* seedlings to NaCl stress. *Scientia Silvae Sinicae*, 2022, 58(1): 32-42. <https://doi.org/10.11707/j.1001-7488.20220104>
- [39] Shao Q, Wang W, Wang J, Yi M, Zhang D, Xie Q. Effects of mixed saline-alkaline stress on seed germination and physiological indices of *Medicago sativa*. *Seed*, 2026, 45(6): 97-104.
- [40] You J, Wang W, Lu J, Jia P, Miao J, Yang Y. Effects of salinity on seed germination and seedling growth in halophyte *Limonium aureum* (L.) Hill. *Acta Ecologica Sinica*, 2012, 32(12): 3825-3833. <https://doi.org/10.5846/stxb201109181369>
- [41] Lu C, Liu Y, Wu J, Yuan Z, Hu R, Zhang S, Wang X, Cao C, Zhang B, Lu H. Response of different potato cultivar seedlings to NaHCO₃ stress and the screening of indicators for anti-NaHCO₃ stress. *Journal of Plant Nutrition and Fertilizers*, 2024, 30(4): 745-756. <https://doi.org/10.11674/zwyf.2023531>
- [42] Lin Q, Zhu X, Mao P, Zhu L, Guo L, Li Z, Cao B, Hao Y, Tan H, Hong P, Lu X. Effects of NaCl and PEG stresses on germination and seedling growth of *Robinia pseudoacacia* seeds with different sizes. *Scientia Silvae Sinicae*, 2022, 58(2): 100-112.
- [43] Pei Y, Qi X, Liu F, Wang L, Nie J, Yang X, Zhang W, Mao J. Effect of NaCl and NaHCO₃ stress on the seeds germination of *Fagopyrum esculentum*. *Seed*, 2016, 35(11): 13-18. <https://doi.org/10.11686/cyxb20120504>
- [44] Cai X, Sun L, Cao X, Zhang F. Effects of NaHCO₃ stress on photosynthetic characteristics and sodium and potassium ions of oilseed rape seedlings with different salt tolerances. *Pratacultural Science*, 2025, 42(9): 2275-2285. <https://doi.org/10.11829/j.issn.1001-0629.2024-0226>
- [45] Wang G, Guo W, Gou Q. Effects of sodium salt stress on seed germination of typical annuals in a desert-oasis ecotone of Hexi Corridor, China. *Chinese Journal of Applied Ecology*, 2020, 31(6): 1941-1947. <https://doi.org/10.13287/j.1001-9332.202006.006>
- [46] Pan P, Ni Q, Ma R, Yang Y, Ma Y. Effects of different salt treatments on seed germination and seedling growth of *Lycium ruthenicum* Murr. *Acta Agrestia Sinica*, 2021, 29(2): 342-348. <https://doi.org/10.11733/j.issn.1007-0435.2021.02.016>
- [47] Lei C, Ji X, Peng M, Jiang L. Effects of sodium salinity stress types on the germination of *Kalidium foliatum* seeds and its young seedling growth. *Arid Zone Research*, 2021, 38(5): 1436-1441. <https://doi.org/10.13866/j.azr.2021.05.26>
- [48] Gui J, Zhao Y, Liu W, Wang B, Wang X, Chen L, Wei X. Effects of exogenous 2, 4-epibrassinolide on seed germination and seedling growth of quinoa under saline-alkali stress. *Chinese Journal of Grassland*, 2025, 47(10): 34-43. <https://doi.org/10.16742/j.zgdx.20250103>
- [49] Xu J, Yang J, Xu Z, Zhao D, Hu X. Exogenous spermine-induced expression of SISPMS gene improves salinity-alkalinity stress tolerance by regulating the antioxidant enzyme system and ion homeostasis in tomato [J]. *Plant Physiology and Biochemistry*, 2020, 157: 79-92. <https://doi.org/10.1016/j.plaphy.2020.09.033>
- [50] Li Z, Zhang W, Cui Y. Effects of NaCl and Na₂CO₃ stresses on seed germination and seedling growth of *Quercus variabilis*. *Acta Ecologica Sinica*, 2015, 35(3): 742-751. <https://doi.org/10.5846/stxb201304190747>
- [51] Baskin J, Lu J, Baskin C, Tan D, Wang L. Diaspore dispersal ability and degree of dormancy in heteromorphic species of cold deserts of northwest China: A review. *Perspectives in Plant Ecology, Evolution and Systematics*. 2014, 16(2): 93-99. <https://doi.org/10.1016/j.ppees.2014.02.001>
- [52] Larios E, Búrquez A, Becerra J, Venable D. Natural selection on seed size through the life cycle of a desert annual plant. *Ecology*, 2014, 95, 3213-3220. <https://doi.org/10.1890/13-1965.1>
- [53] Wu M, Cao B. Studies on germination and physiological characteristics of *Fraxinus velutina* seeds from salt and normal soils. *Seed*, 2006, 25(4): 4-7.
- [54] Liang Y, Du J, Qin X, Yang Y, Sun W, Yao L, Su S, Gao G, Huang L. Effects of seed size and hardness degree on imbibition and germination of *Sophora japonica* seeds. *Shandong Forestry science and technology*, 2025, (3): 7-14.
- [55] Wang M, Zhu X, Liu W, Wang K, Tan C, Liu G, Mao P, Cao B, Jia B, Pang Y, Jiang F. Natural regeneration of *Morus alba* in *Robinia pseudoacacia* plantation and the mechanism of seed germination and early seedling growth restriction in the Yellow River Delta [J]. *Water*, 2023, 15(3): 546. <https://doi.org/10.3390/w15030546>
- [56] Liu G, Qiao J, Liang Y, Qin X, Mao P, Du X, Yang J, Cao X, Cao B, Yang Q, Lu X, Li X. Study on the difference of salt tolerance capacity between saline-alkali land and non-saline-alkali land of *Ulmus pumila* seeds based on tree age. *Seed*, 2025, 44(4): 210-219. <https://doi.org/10.16590/j.cnki.1001-4705.2025.04.210>