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# EFFECTS OF SALT STRESS ON VARIOUS MORPHOPHYSIOLOGICAL PROCESSES IN BARLEY PLANTS

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The effects of sodium-izocation salinity (NaCl and $Na_2SO_4$) on germination parameters, morphometric traits, water status, and the content of photosynthetic pigments during the early stages of ontogenesis in barley (*Hordeum vulgare* L.) cultivated under water and soil culture conditions were studied comparatively.

It was found that with increasing salt concentration, the germination percentage and germination energy of seeds, root and shoot length, tolerance index, moisture parameters, relative water content, as well as chlorophyll a and chlorophyll b contents decreased sharply. The increase in the amount of carotenoids was not marked at relatively low salt concentrations (25-50 mM), and the decrease in the amount of carotenoids was not pronounced with a subsequent increase in the concentration (75-100 mM). It was revealed that the increase in carotenoid content under prolonged salt stress is associated with its protective function. Thus, carotenoids protect cells against the formation of reactive oxygen species. It was also found that chloride salinity exerted a stronger inhibitory effect in soil culture, whereas sulfate salinity had a more pronounced inhibitory effect in water culture.

Barley plants were found to be tolerant to low and moderate salinity conditions. However, at high salt concentrations, a sharp decline in physiological parameters was observed. The obtained results demonstrated that different adaptation mechanisms depend on the type and concentration of salts, cultivation conditions, and the duration of stress exposure.

**Keywords:** Salt stress, barley seedlings, photosynthetic pigments, morphometric parameters, growth parameters

## INTRODUCTION

Soil salinization is currently considered one of the major abiotic stress factors limiting the sustainable development of agriculture on a global scale [14]. Recent studies indicate that a significant proportion of cultivated lands worldwide is affected by salinization to varying degrees, and this process is further accelerated by climate change, disruption of irrigation regimes, and anthropogenic impacts [1, 8, 15]. The effects of salt stress on plants are mainly exerted through three principal mechanisms: osmotic stress, ion toxicity, and oxidative stress [1, 2,4, 11, 19].

At low concentrations, the osmotic effect of salts on plants does not cause drastic changes in metabolism, but it has been found that the toxic effect of salts is the factor exerting a more negative impact on plants [1].

High concentrations of salts reduce the water potential in plant cells, making water uptake more difficult. As a result, seed germination and early developmental stages are significantly inhibited. Furthermore, the accumulation of $Na^+$ and $Cl^-$ ions adversely affects metabolic processes and disrupts the activity of enzyme systems [1, 10, 12, 13]. Under these conditions, the levels of reactive oxygen species -

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superoxide anion ($O_2^-$), hydrogen peroxide ($H_2O_2$), and hydroxyl radical (OH•), increase, leading to oxidative damage in cellular structures [5, 24].

The impact of salt stress varies depending on the plant species, developmental stage, chemical nature of the salt, and cultivation conditions. For example, NaCl and $Na_2SO_4$ salts exert different mechanisms of action on plants, and their comparative study allows for a deeper understanding of salt tolerance issues [23, 25]. Besides, studies conducted under both hydroponic and soil culture conditions show that environmental factors significantly change the intensity of salt effects on plants [5, 23].

In this context, the study aimed to comprehensively investigate the effects of different concentrations of sodium-izocation salts on germination parameters, morphometric traits, the photosynthetic pigment system, and water status in barley, as well as to determine the relationship between these changes and the plants' adaptive mechanisms.

## MATERIALS AND METHODS

Seeds and 7-day-old seedlings of the Garabagh 22 variety of barley (*Hordeum vulgare* L.) were used as the research material. The seeds were pre-selected to obtain uniform, healthy specimens, surface-sterilized in a 0.1% potassium permanganate solution, and then rinsed with distilled water [3].

The experiments were conducted under two different conditions: hydroponic culture and soil culture. In the hydroponic setup, seeds were germinated on filter paper in Petri dishes and treated with the respective salt solutions. In the soil culture, the seeds were sown in artificially salinized soil prepared prior to the experiment.

To induce salt stress, different concentrations of NaCl and $Na_2SO_4$were applied. In the hydroponic culture, concentrations of 25, 37.5, 50, 75, and 100 mM were used, whereas in the soil culture, concentrations of 0.2%, 0.4%, 0.6%, 0.8%, and 1% were applied. The control variant consisted of distilled water and non-salinized soil conditions.

**Seed germination energy and germination percentage** were determined according to international standard methods. Germination energy was calculated as the percentage of seeds that germinated within a specific time interval, while total germination was calculated based on the total number of seeds that germinated by the end of the experiment [9].

**Morphometric parameters** were determined using the ImageJ software [7].

**The tolerance index** was calculated using the following formula:

TI (%) = (plant length under stress conditions / control variant) × 100 [6].

**Relative Water Content (RWC) and water deficit** were used to evaluate the water status of the plants and were calculated based on the following formula (Barrs & Weatherley modification):

RWC (%) = (FW – DW) / (TW – DW) × 100.

where FW represents fresh weight, TW is turgid weight, and DW is dry weight [26].

**Dry biomass** was determined by drying the samples at 105°C until a constant weight was achieved. Moisture content was calculated as a percentage based on the difference between fresh and dry weights [27].

**The content of photosynthetic pigments-chlorophyll a, chlorophyll b, and carotenoids** was determined based on a modified version of the method of Lichtenthaler (1987). For this purpose, approximately 0.1 g of fresh green plant material was homogenized in a mortar with 5 mL of 96% ethanol. To accelerate the process, quartz sand ($SiO_2$) was added, and calcium carbonate ($CaCO_3$) was included to precipitate phenolic compounds. The obtained homogenate was filtered through filter paper into a 25 mL flask, and the volume was adjusted to 25 mL with ethanol [18].

The concentrations of chlorophyll a, chlorophyll b, and carotenoids were calculated according to the Holm-Wettstein equations.

Chl a = 9.784 * D662-0.990 * D644 (mg \ l)

Chl b = 21.426 * D644-4.650 * D662 (mg \ l)

Car = 4.695 * D440.5-0.268 (a + b) (mg \ l)

Note*: All experiments were performed in 3-4 replicates, and the obtained results are presented as mean values ± standard error (Mean ± SE).

## RESULTS AND DISCUSSION

Based on the results of the study, both germination energy and germination percentage were 100% in the control variant under both hydroponic and soil culture conditions. With increasing salinity, a gradual decrease in these parameters was observed in both environments. Under NaCl treatment, germination parameters remained relatively higher in hydroponic culture: at 25 mM concentration, germination energy was 90% and germination percentage was 94%, whereas at 100 mM these values decreased to 62% and 67%, respectively. In soil culture, the effect of NaCl was more pronounced. Thus, at 0.2% concentration, germination energy and germination percentage were 82% and 87%, respectively, while at 1% these values decreased to 25% and 28%. This indicates that NaCl salinity exerts a stronger inhibitory effect under soil conditions (Figure 1).

In contrast, a different pattern was observed under $Na_2SO_4$ treatment. In hydroponic culture, at a concentration of 25 mM, germination energy was 86% and germination percentage was 90%, whereas at 100 mM these values sharply decreased to 31% and 33%, respectively. In soil culture, the effect of NaCl was more pronounced, with germination energy at 0.2% being 82% and germination percentage being 87%, while at 1% these parameters were 25% and 28%. These results indicate that $Na_2SO_4$ salinity has a stronger effect in the aqueous medium, while its impact is relatively weaker under soil conditions. Consequently, NaCl exerts a more pronounced inhibitory effect on germination in soil culture, whereas $Na_2SO_4$ shows a stronger negative effect in hydroponic culture.

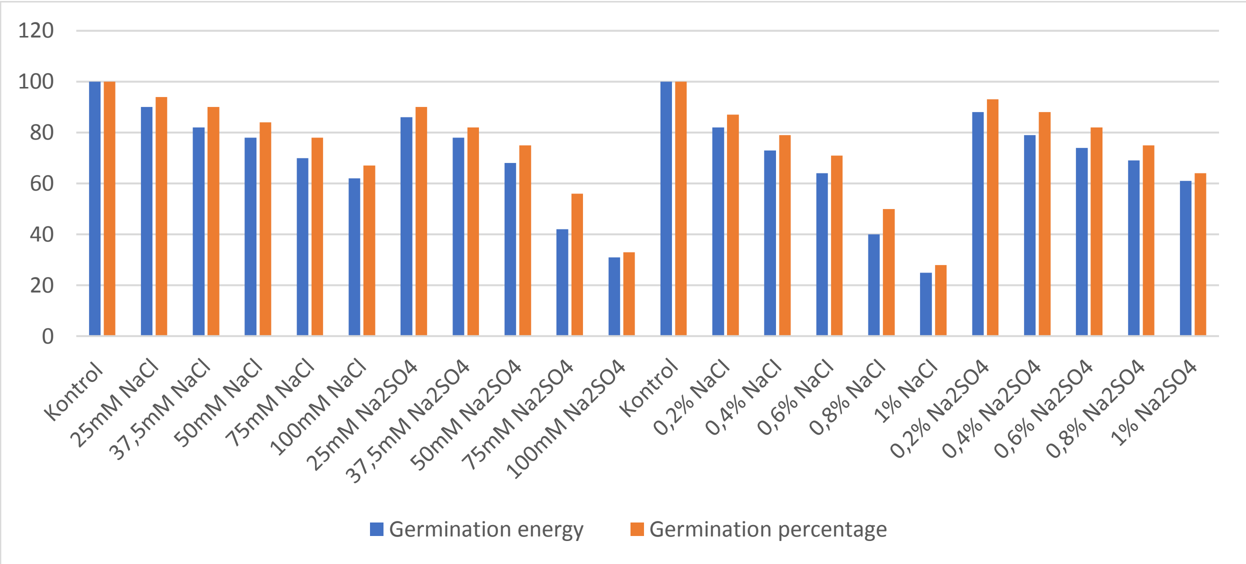


**Figure 1.** Germination percentage and germination energy of barley seedlings grown in hydroponic and soil cultures

Increasing the concentration of salts significantly reduces seed germination parameters, and this effect varies depending on both the type of salt and the cultivation conditions [19, 22, 23]. Although the impact is relatively mild at low and moderate concentrations, a sharp inhibition of the germination process is observed at higher concentrations [12]. This confirms that salinity stress exerts a strong negative effect on the early developmental stages of plants, as they are more sensitive to salinity during the initial phases of ontogenesis [29].

Determination of growth parameters

According to the research results, under both water and soil culture conditions, an increase in salt concentrations in barley seedlings led to a consistent decline in all morphometric parameters: total seedling length, root and shoot length, as well as the tolerance index (Figure 2).

In water culture, the effect of NaCl was relatively weaker. Thus, while the seedling length in the control variant was 19.9 cm, it decreased only slightly to 18.3 cm under 25 mM NaCl treatment (approximately a 1.1-fold reduction), and to 9.2 cm at 100 mM (approximately a 2.2-fold reduction). The same trend was observed for both root and shoot lengths. The tolerance index decreased from 91.25% to 46.23%, indicating that the plant retained a certain level of tolerance (Table 1).

Under $Na_2SO_4$ treatment, a more pronounced decrease was recorded in the water culture. At 25 mM concentration, seedling length decreased to 10.2 cm (approximately a 2-fold reduction), and at 100 mM it dropped to only 1.4 cm (approximately a 14-fold reduction). Root and shoot lengths showed a similarly sharp decline, while the tolerance index decreased from 51.25% to 7.03%. These results indicate that, in an aqueous environment, sulfate salinity exerts a stronger inhibitory effect compared to chloride salinity [17].

In soil culture, a different pattern was observed. The effect of NaCl was more pronounced under these conditions. While the seedling length in the control variant was 20.4 cm, it decreased to 10.8 cm under 0.2% NaCl treatment (approximately a 2-fold reduction) and to 0.8 cm at 1% (approximately a 25-fold reduction). The tolerance index also decreased accordingly from 52.94% to 3.92%. This indicates that NaCl acts as a very strong stress factor under soil conditions.

$Na_2SO_4$, in contrast, exhibited a relatively weaker effect in soil culture. At a concentration of 0.2%, the seedling length was 18.8 cm (close to the control), while at 1% it decreased to 9.3 cm (approximately a 2.2-fold reduction). The tolerance index declined from 92.15% to 45.58%, indicating that the plant demonstrates higher tolerance to this salt under soil culture conditions.

The results indicate that in barley, NaCl exerts a stronger inhibitory effect in soil culture, whereas $Na_2SO_4$ shows a more pronounced inhibitory effect in water culture [12, 23]. This difference may be explained by the behavior of ions in the medium and their uptake characteristics by the plant [19, 28, 29].

a) b)

**Figure 2.** Barley seedlings grown under NaCl (a) and $Na_2SO_4$ (b) salinity conditions in water and soil cultures

**Table 1.** Growth parameters and tolerance index of barley seedlings grown in water and soil cultures

| Variants | Seedling length, cm | Root length, cm | Shoot length, cm | Tolerance index, % |
|---|---|---|---|---|
| Control | 19.9±0.9 | 8.9±0.32 | 11±0.43 | |
| 25mM NaCl | 18.3±0.8 | 8.2±0.31 | 10.1±0.41 | 91.25±4.1 |
| 37,5mM NaCl | 17±0.7 | 7.8±0.31 | 9.2±0.33 | 85.4±3.6 |
| 50mM NaCl | 15.5±0.6 | 7±0.3 | 8.5±0.32 | 77.88±3.1 |
| 75mM NaCl | 11.8±0.4 | 5.8±0.24 | 6±0.2 | 59.29±3.0 |

| | | | | |
|---|---|---|---|---|
| 100mM NaCl | 9.2±0.35 | 4.1±0.24 | 5.1±0.26 | 46.23±2.1 |
| 25mM $Na_2SO_4$ | 10.2±0.36 | 3.2±0.14 | 7±0.0.31 | 51.25±2.2 |
| 37.5mM $Na_2SO_4$ | 7.7±0.31 | 2.7±0.12 | 5.01±0.22 | 38.69±1.9 |
| 50mM $Na_2SO_4$ | 5.3±0.21 | 1.8±0.07 | 3.5±0.13 | 26.63±1.6 |
| 75mM $Na_2SO_4$ | 2.9±0.14 | 1.1±0.05 | 1.8±0.07 | 14.57±0.9 |
| 100mM $Na_2SO_4$ | 1.4±0.06 | 0.6±0.03 | 0.8±0.03 | 7.03±0.32 |
| Control | 20.4±0.8 | 8.4±0.33 | 12±0.41 | |
| 0.2% NaCl | 10.8±0.4 | 3±0.11 | 7.8±0.21 | 52.94±0.2 |
| 0.4% NaCl | 8.8±0.35 | 2.6±0.1 | 6.2±0.2 | 43.13±1.9 |
| 0.6% NaCl | 5±0.2 | 1.2±0.05 | 3.8±0.17 | 24.5±0.77 |
| 0.8% NaCl | 2.8±0.1 | 0.9±0.05 | 1.9±0.08 | 13.72±0.44 |
| 1% NaCl | 0.8±0.02 | 0.4±0.02 | 0.4±0.02 | 3.92±0.13 |
| 0.2% $Na_2SO_4$ | 18.8±0.7 | 7.8±0.32 | 11±0.46 | 92.15±4.1 |
| 0.4% $Na_2SO_4$ | 17.2±0.62 | 7±0.31 | 10.2±0.44 | 84.31±3.7 |
| 0.6% $Na_2SO_4$ | 15.4±0.5 | 6.7±0.26 | 8.7±0.35 | 75.49±3.2 |
| 0.8% $Na_2SO_4$ | 12.4±0.4 | 5.5±0.2 | 6.9±0.31 | 60.78±2.7 |
| 1% $Na_2SO_4$ | 9.3±0.3 | 3.9±0.13 | 5.4±0.21 | 45.58±2.0 |

*Note: The coefficient of variation (Cs) was below 5%.

Calculation of fresh and dry biomass

According to the research results, an increase in salinity in barley seedlings, both in water and soil cultures, is accompanied by an increase in dry biomass and a decrease in moisture content. However, the intensity of these changes varies depending on the growth medium and the type of salt (Table 3).

**Table 3.** Fresh and dry biomass of barley seedlings grown in water and soil cultures

| Variants | Dry biomass, % | | Moisture, % | |
|---|---|---|---|---|
| | Shoots | Roots | Shoots | Roots |
| Control | 5.58±0.22 | 4.44±0.21 | 94.42±3.7 | 95.56±3.8 |
| 25mM NaCl | 6.42±0.26 | 5.38±0.22 | 93.58±3.6 | 94.62±3.8 |
| 37.5mM NaCl | 7.01±0.3 | 5.91±0.23 | 92.99±3.6 | 94.01±3.8 |
| 50mM NaCl | 7.87±0.35 | 6.52±0.25 | 92.13±3.6 | 93.48±3.6 |
| 75mM NaCl | 8.72±0.32 | 7.13±0.3 | 91.28±3.5 | 92.87±3.6 |
| 100mM NaC | 9.46±0.33 | 8.02±0.31 | 90.54±3.5 | 91.98±3.5 |
| 25mM $Na_2SO_4$ | 6.89±0.3 | 5.93±0.24 | 93.11±3.6 | 94.07±3.6 |
| 37.5mM $Na_2SO_4$ | 7.61±0.32 | 6.59±0.3 | 92.39±3.6 | 93.41±3.6 |
| 50mM $Na_2SO_4$ | 8.73±0.33 | 7.12±0.3 | 91.27±3.5 | 92.88±3.6 |
| 75mM $Na_2SO_4$ | 9.64±0.34 | 7.81±0.31 | 90.36±03.5 | 92.19±3.6 |
| 100mM $Na_2SO_4$ | 10.86±0.36 | 8.63±0.33 | 89.14±3.4 | 91.37±3.5 |
| Control | 4.79±0.21 | 3.56±0.15 | 95.21±3.8 | 96.44±3.8 |
| 0.2% NaCl | 5.79±0.22 | 4.79±0.21 | 94.21±3.8 | 95.21±3.8 |
| 0.4% NaCl | 6.54±0.26 | 5.30±0.22 | 93.46±3.6 | 94.7±3.8 |
| 0.6% NaCl | 7.59±0.3 | 7.47±0.3 | 92.41±0.36 | 92.53±3.6 |
| 0.8% NaCl | 9.23±0.33 | 9.39±0.33 | 90.77±0.35 | 91.61±3.5 |
| 1% NaCl | 11.32±0.51 | 9.96±0.33 | 88.68±3.4 | 90.04±3.5 |
| 0.2% $Na_2SO_4$ | 5.29±0.22 | 4.22±0.2 | 94.71±3.8 | 95.78±3.8 |
| 0.4% $Na_2SO_4$ | 6.44±0.26 | 4.99±0.21 | 93.56±3.6 | 95.01±3.8 |
| 0.6% $Na_2SO4$ | 7.27±0.3 | 6.73±0.26 | 92.73±3.6 | 93.27±3.6 |
| 0.8% $Na_2SO_4$ | 8.96±0.31 | 7.69±0.3 | 91.04±3.5 | 92.31±3.6 |
| 1% $Na_2SO_4$ | 10.81±0.5 | 8.54±0.31 | 89.19±3.4 | 91.46±3.5 |

*Note: The coefficient of variation (Cs) was below 5%

In water culture, under the effect of NaCl, dry biomass increased from 5.58% to 9.46% in the shoots and from 4.44% to 8.02% in the roots, while moisture content decreased from 94.42% to 90.54% and from 95.56% to 91.98%, respectively. Under $Na_2SO_4$treatment, these changes were more pronounced: dry biomass increased to 10.86% in the shoots and 8.63% in the roots, while moisture content decreased to 89.14% and 91.37%, respectively. This indicates that $Na_2SO_4$exerts a stronger effect than NaCl in the aqueous medium.

In soil culture, in the control variant, dry biomass was 4.79% in the shoots and 3.56% in the roots, while moisture content was 95.21% and 96.44%, respectively. Under NaCl treatment, the effect was more pronounced: dry biomass increased to 11.32% in the shoots and 9.96% in the roots, while moisture content decreased to 88.68% and 90.04%, respectively.

$Na_2SO_4$ exhibited a relatively weaker effect in soil culture. Thus, dry biomass reached 10.81% in the shoots and 8.54% in the roots, while moisture content decreased to 89.19% and 91.46%, respectively.

Comparatively, it can be concluded that sulfate salinity in water culture and chloride salinity in soil culture exert stronger effects, leading to a more pronounced relative increase in dry matter and a greater reduction in moisture content [19, 23]. This difference can be explained by ion mobility in the medium and their uptake characteristics by the plant [12, 29].

Determination of RWC and water deficit

According to the research results, in barley seedlings grown in both water and soil cultures, increasing salt concentrations leads to a decrease in RWC, an increase in water deficit, and a reduction in leaf surface area. However, the extent of these changes varies depending on the type of salt and the growth medium (Table 4).

Under the effect of NaCl in water culture, the relative water content was 68%, while water deficit increased to 32%. Besides, leaf area decreased from 4.3 $cm^2$ to 2.2 $cm^2$. Under $Na_2SO_4$treatment, these changes were somewhat less pronounced: RWC decreased to 77%, water deficit increased to 23%, while leaf area declined more sharply to 1.3 $cm^2$. This indicates that although NaCl has a stronger effect on water balance in the aqueous medium, $Na_2SO_4$ exerts a more pronounced effect on the reduction of leaf area.

**Table 4.** Determination of RWC, water deficit, and leaf area of barley seedlings grown in water and soil cultures

| | RWC,% | Water deficit, % | Leaf area, $cm^2$ |
|---|---|---|---|
| Control | 100 | 0 | 4.3 ±0.22 |
| 25mM NaCl | 91 ±3.5 | 9 ±0.33 | 4 ±0.21 |
| 37.5mM NaCl | 86 ±3.4 | 14 ±0.44 | 3.8 ±0.2 |
| 50mM NaCl | 80 ±3.2 | 20 ±0.9 | 3.7 ±0.19 |
| 75mM NaCl | 74 ±3.0 | 26 ±1.1 | 3.1 ±0.14 |
| 100mM NaCl | 68 ±2.9 | 3 ±0.14 | 2.2 ±0.13 |
| 25mM $Na_2SO_4$ | 93 ±3.6 | 7 ±0.32 | 3.7 ±0.19 |
| 37.5mM $Na_2SO_4$ | 89 ±3.4 | 11 ±0.37 | 3 ±0.14 |
| 50mM $Na_2SO_4$ | 85 ±3.3 | 15 ±0.5 | 2.4 ±0.13 |
| 75mM $Na_2SO_4$ | 81 ±3.3 | 19 ±0.9 | 2 ±0.12 |
| 100mM $Na_2SO_4$ | 77 ±3.1 | 23 ±1.0 | 1.3 ±0.06 |
| Control | 100 | 0 | 4.5±0.22 |
| 0.2% NaCl | 92±3.4 | 8±0.33 | 3.9±0.21 |
| 0.4% NaCl | 88±3.3 | 12±0.42 | 3.3±0.15 |
| 0.6% NaCl | 83±3.2 | 17±0.62 | 2.7±0.12 |
| 0.8% NaCl | 78±3.1 | 22±1.0 | 2.4±0.13 |
| 1% NaCl | 71±3.0 | 29±1.7 | 1.8±0.07 |
| 0.2% $Na_2SO_4$ | 95±3.6 | 5±0.22 | 4.1±0.21 |
| 0.4% $Na_2SO_4$ | 91±3.5 | 9±0.25 | 3.8±0.21 |
| 0.6% $Na_2SO_4$ | 87±3.3 | 13±0.1 | 3.2±0.15 |
| 0.8% $Na_2SO_4$ | 84±3.2 | 16±0.01 | 3±0.14 |

| | | | |
|---|---|---|---|
| 1% $Na_2SO_4$ | 80±3.1 | 25±0.35 | 2.5±0.1 |

In soil culture, although the general trend was maintained, the intensity of the effects differed. Under NaCl treatment, RWC decreased to 71%, water deficit increased to 29%, and leaf area was reduced to 1.8 cm². Under $Na_2SO_4$treatment, RWC remained at a relatively higher level (80%), water deficit increased less markedly (25%), and leaf area decreased to a lesser extent (2.5 cm²) [1].

The conducted studies have demonstrated that NaCl disrupts water balance more severely in both media, particularly in soil culture, leading to a greater increase in water deficit [23].

In contrast, $Na_2SO_4$exerts a stronger effect on the reduction of leaf area in water culture, while its impact in soil is relatively weaker [12]. Overall, increasing salt concentrations in barley is accompanied by disturbances in the water status and a reduction in the photosynthetic surface area. This effect is more pronounced for NaCl under soil conditions and for $Na_2SO_4$in aqueous environments [21].

Determination of photosynthetic pigments

According to the research results, in 7-day-old barley seedlings, the content of photosynthetic pigments varied in different directions depending on the type and concentration of salt in both water and soil cultures (Table 5).

In water culture, under NaCl treatment, a consistent decrease in the content of chlorophyll a, chlorophyll b, and carotenoids was observed with increasing concentration. Thus, chlorophyll a decreased from 25.509 to 7.845, chlorophyll b from 10.771 to 1.93, and carotenoids from 15.557 to 6.147. The total chlorophyll content (a + b) also declined from 36.28 to 9.775. At the same time, the chlorophyll a/b ratio increased from 2.368 to 4.064, indicating a more rapid degradation of chlorophyll b.

Under $Na_2SO_4$ treatment in water culture, a different pattern was observed: chlorophyll b content was higher than chlorophyll a, and the total chlorophyll content (a + b) remained at a relatively higher level compared with NaCl treatment, decreasing from 45.546 to 18.71. However, with increasing salt concentration, a reduction was still recorded in all pigments. The chlorophyll a/b ratio being below 1 indicates the predominance of chlorophyll b.

**Table 5.** Content of photosynthetic pigments in 7-day-old barley seedlings grown in water and soil cultures

| Variants | Control | 25mM | 37.5mM | 50mM | 75mM | 100mM |
|---|---|---|---|---|---|---|
| Chl a (NaCl) | 25.509 | 25.173 | 20.012 | 19.264 | 12.054 | 7.845 |
| Chl b (NaCl) | 10.771 | 10.476 | 6.555 | 5.488 | 3.177 | 1.93 |
| Car (NaCl) | 15.557 | 15.447 | 13.46 | 12.559 | 8.712 | 6.147 |
| **Chl a+b (NaCl)** | **36.28** | **35.649** | **26.567** | **24.752** | **15.231** | **9.775** |
| **Chl a\b (NaCl)** | **2.368** | **2.402** | **3.052** | **3.510** | **3.749** | **4.064** |
| Chl a ($Na_2SO_4$) | 15.557 | 14.478 | 12.904 | 9.97 | 9.591 | 6.214 |
| Chl b ($Na_2SO_4$) | 29.989 | 25.648 | 22.963 | 20.94 | 15.217 | 12.496 |
| Car ($Na_2SO_4$) | 10.802 | 8.065 | 6.222 | 4.789 | 3.018 | 2.314 |
| **Chl a+b** ($Na_2SO_4$) | **45.546** | **40.126** | **35.867** | **30.91** | **24.808** | **18.71** |
| **Chl a\b**($Na_2SO_4$) | **0.518** | **0.564** | **0.561** | **0.476** | **0.630** | **0.497** |
| **Variants** | **Control** | **0.2%** | **0.4%** | **0.6%** | **0.8%** | **1%** |
| Chl a (NaCl) | 13.757 | 16.634 | 17.064 | 13.804 | 11.829 | 7.631 |
| Chl b (NaCl) | 3.852 | 4.58 | 4.769 | 3.892 | 2.29 | 1.356 |
| Car (NaCl) | 10.422 | 10.571 | 11.481 | 6.892 | 5.623 | 3.265 |
| **Chl a+b (NaCl)** | **17.609** | **21.214** | **21.833** | **17.696** | **14.119** | **8.987** |
| **Chl a\b (NaCl)** | **3.571** | **3.631** | **3.578** | **3.546** | **5.165** | **5.627** |
| Chl a ($Na_2SO_4$) | 13.757 | 15.11 | 15.233 | 17.347 | 15.36 | 14.82 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Chl b ($Na_2SO_4$) | 3.852 | 5.61 | 5.988 | 5.115 | 4.968 | 4.006 |
| Car ($Na_2SO_4$) | 10.422 | 10.468 | 10.744 | 10.814 | 10.399 | 9.994 |
| **Chl a+b (**$Na_2SO_4$**)** | **17.609** | **20.72** | **21.221** | **22.462** | **20.32** | **28.826** |
| **Chl a\b (**$Na_2SO_4$**)** | **3.571** | **2.693** | **2.543** | **3.391** | **3.091** | **3.699** |

*Note: The coefficient of variation (Cs) was below 5%

In soil culture, NaCl treatment initially led to a certain increase in pigment content at lower concentrations. For instance, chlorophyll a increased from 13.757 to 17.064, and total chlorophyll (a + b) rose to 21.833. However, with increasing salt concentration, these parameters decreased sharply, reaching minimum levels at the highest concentration (100mM, 1%). In the case of carotenoids, different results were obtained. Thus, their content increased at low salt concentrations, whereas a decrease was observed at high concentrations.

In soil culture, $Na_2SO_4$exerted a more stable effect. The contents of chlorophyll a and b, as well as carotenoids, were maintained at relatively high levels over a wide range of concentrations. In some variants, the total chlorophyll (a + b) even showed an increase. This indicates that sulfate salts have a weaker destructive effect on the photosynthetic apparatus under soil conditions [4, 30].

In water culture, NaCl had a stronger inhibitory effect on photosynthetic pigment content, whereas $Na_2SO_4$showed a comparatively weaker effect. In soil culture, however, the opposite trend was observed: NaCl caused a sharp decline at high concentrations, while $Na_2SO_4$ helped maintain more stable pigment levels. These differences can be explained by the ionic composition of the salts, ionic strength, ion activity, ion activity coefficient, and their uptake characteristics by plants in media [4, 16, 20].

## CONCLUSIONS

- The results of the study show that increasing salt concentrations significantly suppresses the germination energy and germination percentage of barley seeds, as well as root and shoot development, and this reduction is characterized by a stronger inhibitory effect of NaCl in soil culture and $Na_2SO_4$in water culture.
- The research results indicate that as salt concentration increases, the tolerance index steadily decreases, reflecting the plant's sensitivity to high salt stress and the limitation of its adaptive capacity.
- The results indicate that increasing salt concentrations leads to an increase in dry biomass and a decrease in moisture content in barley seedlings, which is associated with disruption of cellular water balance and intensification of physiological stress.
- The analyses show that increasing salt concentrations disrupts the plant's water balance, reduces RWC, and intensifies water deficit. This effect is more pronounced for NaCl in soil culture and for $Na_2SO_4$ in water culture.
- The research results show that although increasing salt concentrations leads to a sharp decrease in chlorophyll a and chlorophyll b, despite fluctuations, the carotenoid content remains higher than in the control. This is associated with the protective function of carotenoids. An increase in salt concentration and a longer duration of salt stress lead to severe damage to the pigment system of the photosynthetic apparatus.
- The study demonstrates that although barley plants possess a certain capacity to adapt to salt stress, physiological processes are severely disrupted at higher concentrations, and this negative effect varies depending not only on the type of salt but also on the cultivation medium.

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