STUDY OF TOLERANCE AND PHYTODESALINATION POTENTIAL OF WHEAT, OAT, EMMER, AND BARLEY FOR SUSTAINABLE SALINE AGRICULTURE

GHAZARYAN, K. A.[1*] – HARUTYUNYAN, A. S.[1] – KHACHATRYAN, H. E.[2] – SINGH, A.[1] – MINKINA, T. M.[3] – RAJPUT, V. D.[3] – MOVSESYAN, H. S.[1]

[1]Chair of Ecology and Nature Protection, Faculty of Biology, Yerevan State University, Alex Manoogian st. 1, Yerevan 0025, Republic of Armenia
(e-mail: anna.harutyunyan@ysu.am, intmsc.abhi@gmail.com, hasmikmov@ysu.am)

[2]Armenian National Agrarian University, Teryan st. 74, Yerevan 0009, Republic of Armenia
(e-mail: hkhachatryan84@gmail.com)

[3]Academy of Biology and Biotechnology, Southern Federal University, Stachki 194/1, Rostov-on-Don 344090, Russian Federation
(e-mail: tminkina@mail.ru, rajput.vishnu@gmail.com)

[*]Corresponding author
e-mail: kghazaryan@ysu.am; phone: +374-9134-2919

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Abstract. Cultivation of salt-tolerant plants is regarded as an innovative approach for desalination and remediation of salt-impacted agricultural soils. From this point of view, the effects of increasing NaCl concentrations in the root medium on some growth traits and development of wheat, oat, emmer, and barley under hydroponic conditions were studied and the phytodesalination potential of these plants was assessed at the greenhouse facilities of the YSU, Republic of Armenia. Crops were grown at six different degrees of salinity (0, 100, 200, 300, 400, 500 mM NaCl) in a hydroponic system that was set up under greenhouse. The results show that the studied plants have different tolerance to increasing concentrations of NaCl. The negative influence of salinity on main growth parameters, relative electrolytic leakage, leaf succulence, chlorophyll content index, photosynthetic rate, and transpiration rate was expressed stronger in emmer compared with the rest of studied crops. Along with the increase in NaCl concentration in the root medium, simultaneously with the significant increase in Na^+ content in the leaves of emmer, a decrease in K^+ content was observed, whilst in wheat, oat, and barley, on the contrary, the increase in Na^+ in the leaves was accompanied by the increase in K^+ concentrations, which indicated the activation of some physiological adaptation mechanisms. Summarizing our results, we concluded that barley and oat could be suggested as promising crops for saline agriculture and soil phytodesalination, since they are survivable, productive and accumulate large amounts of ions in their above-ground parts.
Keywords: *hydroponic culture, salinity stress, plant salt tolerance, phytodesalination*

Abbreviations. EC: electrical conductivity; FM: fresh mass; DM: dry mass; FM_r/FM_s: root/shoot ratio (fresh mass); DM_r/DM_s): root/shoot ratio (dry mass); RWC%: root water content; SWC%: stem water content; LWC%: leaf water content; FW/DW ratio: water status; REL: relative electrolytic leakage; LS: leaf succulence; CCI: chlorophyll content index; P_n: photosynthetic rate; E: transpiration rate; WUE: water use efficiency; TDS: total dissolved solids

Introduction

Nowadays multiple global problems including climate change, increasing population, environmental pollution, shortage of water and land resources as well as soil salinization hinder sustainable production in agriculture (Dong et al., 2019; Shahid et al., 2019). An expanding population apparently will result in a growth of worldwide demand of food for

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at least the upcoming four decades (Godfray et al., 2010). Scarcity of natural resources, particularly of high-quality arable lands and water resources will depress the potential for food production in some regions (FAO, IFAD and WFP, 2013). In developing countries with coastal, semi-arid and arid areas, soil salinity is a serious threat that can restrict agricultural productivity, food safety, environmental sustainability, and associative values (Deinlein et al., 2014; Yan et al., 2015; Abouelsaad and Renault, 2018; Afridi et al., 2019; Hayat et al., 2020a). According to the World Bank statement, salinization of soil caused by improper practices of irrigation affects around 60 million hectares or 24% of all irrigated agricultural lands in the world (Vengosh, 2003).

Soil salinity has a substantial influence on physiology of plants causing as a rule low osmotic potential, an imbalance in nutrient uptake, specific effects of ions, or a combination of all mentioned effects (Rabhi et al., 2015). These impacts result in a decrease in seed germination (Läuchli and Grattan, 2007; Parihar et al., 2015) and plant growth rate (Aslam et al., 2011; Heintzman et al., 2015). Salinity induces nutrient and water imbalances resulting in inhibition of the formation of younger leaves coupled with accelerated ageing of older leaves, thus decreasing the amount of photosynthetic pigments, inhibiting the productivity and growth rate of some plants, including traditional crops (Shahzad et al., 2017; Abouelsaad and Renault, 2018; Çiçek et al., 2018; Khalid et al., 2018). Salinity influences also the photosynthesis in connection with reduced availability of CO_2 and also oxidative stress or changes in photosynthetic metabolism (Chaves et al., 2009). Under conditions of salt stress a decrease in photosynthetic pigments Chl a and Chl b has been described as a result of reduced biosynthesis or accelerated degradation of pigments.

Plants have evolved several specialized mechanisms of defense in order to endure/withstand stressful situations (Gupta and Huang, 2014). The growth of plants under salinity stress is determined by the ability to maintain low concentrations of sodium ions in the cytoplasm to protect the cells. Plants usually cope with stress induced by salinity either by avoiding the stress or applying the strategies of stress tolerance (Parihar et al., 2015). But plant species that are tolerant to salt stress display either osmotic resistance or tissue tolerance capacities (Rangani et al., 2016; Sarabi et al., 2017).

Based on the response to soil salinity, the plants were differentiated as salt-preferring or salt-tolerant halophytes and salt-sensitive glycophytes (Alam and Sharma, 2017; Liang et al., 2017). Halophytes can grow at levels of salinity above 200 mM NaCl (Flowers and Colmer, 2008), which approximately corresponds to semi-strength seawater. Halophytes have a capability to intensely regulate homeostasis of ions and withstand salt shock. Various morphological, physiological, and biochemical adjustments are developted by halophytes to stand against or even benefit from saline environments (Panta et al., 2014; Flowers and Muscolo, 2015). Facultative halophytes that mediate between glycophytes and halophytes have the ability to grow and fulfill their life cycle in saline as well as in non-saline soils. This group can include both wild plants and various crops. Facultative halophyte crops are able not only to provide sufficient yields in saline soils but can also improve these soils to some extent.

Unlike expensive desalination technologies such as membrane using processes, thermal (distillation) processes, reverse osmosis and electrodialysis (Islam et al., 2019), phytodesalination is a green, cost-efficient technology for the remediation of salt-affected sites and the restoration of agricultutal lands (Hasanuzzaman et al., 2014). Roots of plants used in phytodesalination absorb the salts dissolved in water and transfer them to the stems and leaves of plants. The capability of facultative halophytes to tolerate high levels

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of salinity and withstand heavy drought and some other environmental stresses makes them perfect candidates for phytodesalination of salt-affected soils. This principle can also be checked under hydroponic conditions to evaluate the ability of salt-removing plants to desalinate saline water (Islam et al., 2019). However, the salt removal potential of different crops has not been adequately assessed in hydroponic systems with different concentrations of NaCl. Such studies can be of great value for agricultural lands irrigated with brackish water. The suggestion of growing salt-tolerant plants in agricultural lands irrigated with saline and brakish water is not new (Rozema and Flowers, 2008; Rozema and Schat, 2013). However, progress in this direction was slow and only in some cases the goal has been to develop new crops (Cheeseman, 2016). Within the limits of saline agriculture, the need for water of salt-tolerant crops is met by brackish water, thus reducing the pressure on freshwater resources. On this basis, the following crops were selected for research: wheat, oat, emmer, and barley.

The objectives of this study were: 1) to evaluate the effects of irrigation water with different concentrations of NaCl on growth productivity of certain varieties of some cereals (wheat, oat, emmer, and barley) in hydroponic culture, 2) to analyze the impact of saline stress on growth and development of these plants (fresh mass, dry mass, root/shoot ratio, leaf water content, photosynthetic characteristics etc.), 3) to study the accumulation of Na^+, K^+, Ca^{2+} and Cl^- in roots, stems and leaves of plants, 4) to assess the phytodesalination potential of plants at increasing NaCl concentrations under hydroponic conditions. The results obtained will help to explain thoroughly the adaptation mechanisms that enable these plants to gain different degrees of tolerance to salt stress as well as to determine the possibility of their cultivation in saline soils irrigated with brackish water.

Materials and methods

Experimental design, plant material, growth conditions and salt treatments

The experiments were carried out in 2022 at the greenhouse facilities of the Faculty of Biology, at the Yerevan State University, Republic of Armenia. A hydroponic system was set up with 72 plastic containers (1.7 litre volume). Natural daylight, 25-35 °C and 60-70% relative humidity were the experimental conditions maintained under greenhouse. The following varieties of wheat, oat, emmer, and barley (wheat - Nairi 68, oat - indigenous variety, emmer - indigenous variety Kotayk, barley - Mush) were grown at six different degrees of salinity (n = 3 each). The salt treatment and the harvesting of the plants were implemented in different phenophases of plants, in particular, the salt treatment - at boot stage (*Fig. 1*), and the harvesting - at maturation stage. The described pot experiment under such soilless hydroponic conditions was performed in quite randomized design. Each container was filled with 200 grams of expanded perlite. The expanded perlite was supplied by "Aragats perlite" OJSC (Republic of Armenia). Expanded perlite was obtained as a result of heat treatment of perlite with a density of 1100 kg/m^3 at 850-900 °C. The density of expanded perlite was 120 kg/m^3, and it had good heat-insulating and water-absorbing capacities. Plant seeds were obtained from the seed reserve fund of the Armenian National Agrarian University. Before the sowing, the seeds were disinfected in sodium hypochlorite for one minute and then in distilled water for 5 minutes. The seeds of wheat, barley, emmer, and oat were sown at approximately 2.0 cm depth, 10 seeds in each container. Throughout the whole study, the appropriate amount of 20% Hoagland solution was added to the plants (Hoagland and Arnon, 1950)

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to maintain the moisture saturation of the expanded perlite at 70-80% (the mass of the container with 80% moisture saturation was determined beforehand and every day between 9 a.m. and 10 a.m. all containers were weighed and brought to the initial weight). The pots were reallocated randomly every week to minimize the influence of potential environmental gradients in the growth camera. The plants were grown in the greenhouse for 1.5 months (March 1-April 15, 2022), and the application of NaCl was started then. After 1.5 months of germination, the plants were irrigated with 640 ml total volume (80 ml every other day for 15 days to avoid osmotic shock, 8 times on the whole) of 0, 100, 200, 300, 400, 500 mM NaCl water. The used volume of water was sufficient to balance the amount of NaCl in the substrate. At the same time, the EC and pH of the substrate in each container were kept the same and observed throughout the experiment. Following the salt treatment after 30 days (at the end of May 2022) all plants were collected.

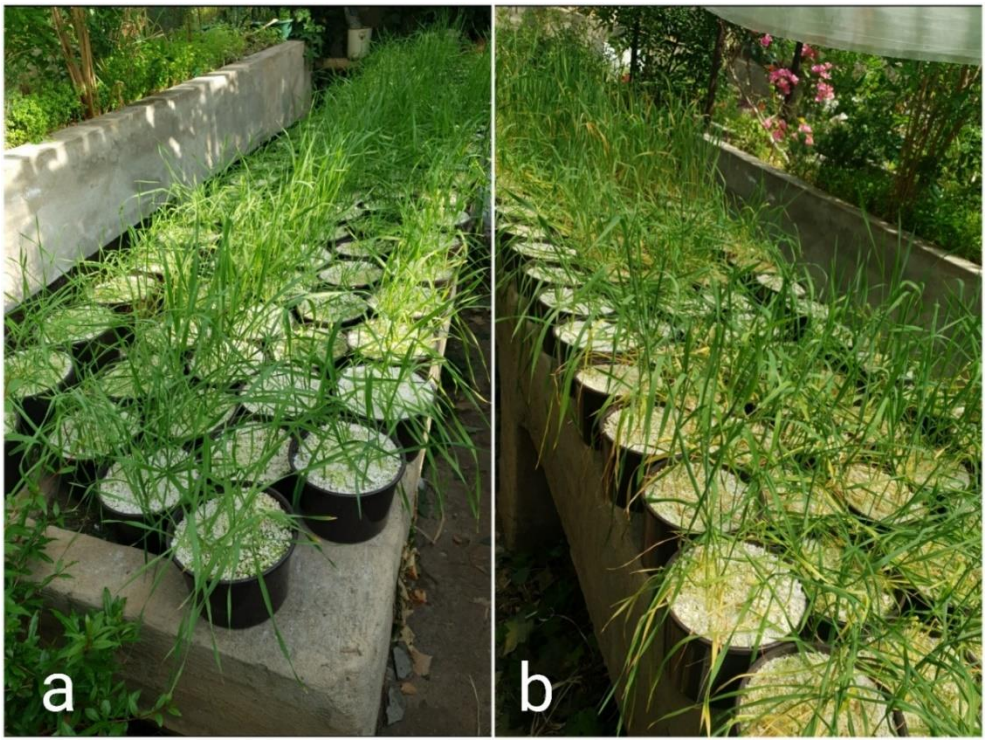

Figure 1. *Plants at the start (a) and at the end (b) of salt treatment*

Growth, biomass yield, morphological and physiological parameters of plants

The shoot height, stem diameter, chlorophyll content index (CCl), photosynthesis and transpiration rates, stomatal conductance, and leaf gas exchange of the seedlings were determined after reaching the required salinity degree of soil before harvesting the plants at 10-day intervals. Plant height, leaf area, fresh mass (FM), dry mass (DM), root/shoot ratio (FM_r/FM_s and DM_r/DM_s), root water content (RWC%), stem water content (SWC%), leaf water content (LWC%), water status (FW/DW ratio), leaf succulence index (LS), relative electrolytic leakage (REL), as well as the contents of some ions in root and shoot were determined after harvesting.

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After 30 days of exposure to NaCl the plants harvested with intact plant root system, were first carefully washed with tap water, then with distilled water to remove traces of substrate cultures. Subsequently the plants were dried with towels before the determination of their fresh mass. Total plant length/height was measured before separation into root and shoot tissues by measuring the distance from the medium surface to the top of the arch of the uppermost leaf. In like manner, morphological parameters including root and shoot fresh mass, shoot length and the length of the longest root, were respectively measured. Then, plant tissues were oven-dried at 70 °C for about 72 hours to reach constant dry mass. Afterwards, dried plant samples were analysed for tolerance capabilities through determination of ion accumulation and flux (Hayat et al., 2020b).

Water contents of roots, stems and leaves

RWC%, SWC% and LWC% were calculated using the following formulas (; Garnier et al., 2001; Slama et al., 2008 Al Hassan et al., 2016a):

$$RWC\% = [(FM_{root} - DM_{root})/FM_{root}] \times 100 \quad \text{(Eq.1)}$$

$$SWC\% = [(FM_{stem} - DM_{stem})/FM_{stem}] \times 100 \quad \text{(Eq.2)}$$

$$LWC\% = [(FM_{leaf} - DM_{leaf})/FM_{leaf}] \times 100 \quad \text{(Eq.3)}$$

where FM_{root}, FM_{stem} and FM_{leaf} are fresh masses of root, stem and leaf, and DM_{root}, DM_{stem} and DM_{leaf} - dry masses of root, stem and leaf, respectively.

Relative electrolytic leakage

The damage of membrane was determined in terms of REL (Dionisio-Sese and Tobita, 1998; González and González-Vilar, 2001). Fresh tissue of leaves (0.5 g) was mixed with 50 ml of distilled water and incubated in test tube for one day at room temperature. The initial electrical conductivity (EC_1) of the medium was measured at the end of the incubation period. Thereafter, the samples were autoclaved for 15 min at 121 °C to release all ions from the tissue. The material was cooled down to room temperature and the final electrical conductivity (EC_2) was recorded. The relative electrolytic leakage was calculated using the following formula:

$$REL=(EC_1/EC_2) \times 100 \quad \text{(Eq.4)}$$

Leaf succulence index

For the calculation of LS the area and fresh weight of ten leaves from each plant were measured. Leaf succulence was calculated as follows (Jennings, 1976; Agarie et al., 2007):

$$LS=LFW/LA \quad \text{(Eq.5)}$$

where LFW is the leaf fresh weight (g) and LA is the leaf area (cm^2).

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Chlorophyll content index

As the indicator of the stressful condition of plants growing in saline soil the chlorophyll contents were determined in expanded leaves from the top of plants under study by means of CCl through the instrumentality of CCM-200 plus Chlorophyll Content Meter (Opti-sciences, USA). Ten measurements were conducted for each plant and the average was immediately calculated by Chlorophyll Content Meter.

Photosynthetic rate (P_n), transpiration rate (E) and water use efficiency (WUE)

P_n and E were measured using a portable photosynthesis system (CI-340) under the conditions of air pressure within a range 89.55-89.90 kPa, air temperature within a range 25-30 °C, and the CO_2 concentration of the air ranged from 390 to 405 μmol mol^{-1}. The measurements were performed on the five young fully expanded leaves (3 replicates for each leaf) from each plant between 9 a.m. and 11 a.m. after 30 days of salt treatment. WUE was recorded as net carbon uptake per amount of water lost from transpiring leaf area and calculated according to Rabhi et al. (2012):

$$WUE = P_n/E \quad \text{(Eq.6)}$$

Ion analysis and total dissolved solids (TDS)

Dried shoots and roots of plants were ground into fine powder and then digested with HNO_3 (0.5%) solution for 30 min at 100 °C for the extraction of ions (one gram of sample - in 100 ml of solution), filtered through a filter paper and immediately analyzed (Zouhaier et al., 2015; Al Hassan et al., 2016b). The concentrations of Na^+, K^+ and Ca^{2+} were measured using a flame photometer (FP-I6431, Bioevopeak, PRC), and the concentration of Cl^- - by a laboratory ionometer (I-160 M, Anatech, Belarus) (5 replicates for each sample).

For the determination of TDS, the samples were autoclaved for 15 min at 121 °C to release all ions from the tissue. The material was cooled down to room temperature and measured by a laboratory ionometer (I-160 M).

Statistical analysis

Statistical analysis was performed using Microsoft Excel 2021 & SPSS-19 software. Statistical significance was determined using Fisher's least significant difference (LSD) test. The error bars in the figures represent 95% confidence intervals.

Results

Effect of NaCl stress on vegetative growth of studied crops

Salinity may have either positive or adverse influence on plant growth parameters such as shoot length, stem diameter, biomass, survivability, and threshold responses depending on salinity level and tolerance of plant (Manousaki and Kalogerakis, 2009). To assess the effect of salinity on plant growth, stem diameter, root, stem, and leaf FM and DM were measured after 30 days of NaCl treatment. Shoot length was measured after each 10 days on completion of NaCl treatment (3 times). According to survivability and threshold responses at different regimes of NaCl stress, the growth and biomass of crops under

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study were significantly affected by treatments with various concentrations of NaCl, however no visible phytotoxic symptoms were observed.

The growth dynamics of shoot length of the crops under conditions of various salt treatments is shown in *Fig. 2*. In general, for all the crops, the height of the plants significantly decreased along with the increase in the concentration of NaCl, but the change in different plant species took place differently (both in terms of time and magnitude). In particular, 10 days after the completion of salt addition, the shoot heights of plants grown in 500 mM NaCl medium compared to control were as follows: oat - 79.6%, emmer - 83.4%, barley - 80.8%, and wheat - 91.8%. Already after 30 days, the dynamics of growth inhibition in crops changed and the maximum growth reduction in plants grown in 500 mM NaCl medium was observed in wheat, then in the following sequence: barley, emmer and oat. The heights of crops compared to control, were 61.0%, 65.8%, 76.6%, and 76.9% respectively.

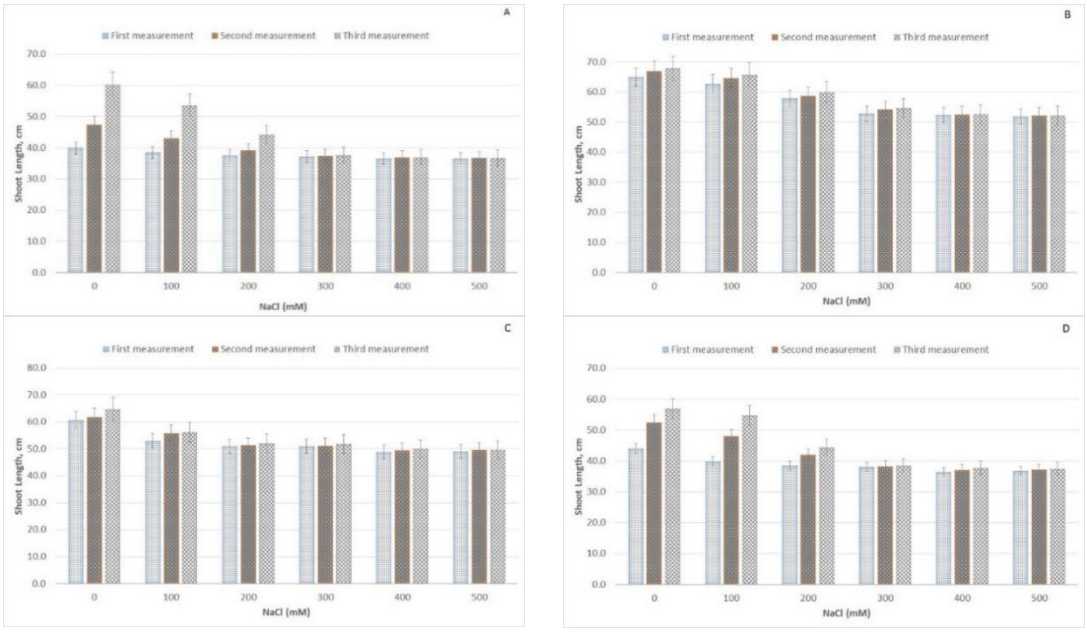

Figure 2. *Effect of NaCl stress on growth of studied crops during salt treatment (A - wheat, B - oat, C - emmer, D - barley, n = 30)*

NaCl treatment affected also the stem diameters of crops (*Fig. 3*). The most significant reduction was observed in emmer followed by wheat. The stem diameter of emmer grown in 400 mM and 500 mM NaCl media reduced by 24.83% compared to control. The stem diameter of wheat grown in the media with the same concentrations of NaCl decreased by almost 18% compared to control, while the stem diameter of oat plants grown in 300 mM, 400 mM, and 500 mM NaCl media reduced by about 11%. However, in the case of barley, the opposite dynamics was observed and an increase in stem diameter took place under the conditions of almost all mentioned concentrations of NaCl.

Effect of NaCl stress on biomass of studied crops

Plant biomass is a significant biological indicator for the assessment of plant tolerance ability to stress caused by NaCl. The results of the study of root, stem, and leaf FM and

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DM of crops are presented in *Table 1*. Maximum fresh and dry masses of root, stem, and leaf of all studied crops were mainly observed in plants grown in 0 mM NaCl medium, and along with the increase in NaCl concentration a decrease in FM and DM was observed. It should be noted that the decrease was mostly not proportionate, and both breakpoints and regaining of fresh and dry masses were observed, and in some cases even a slight increase took place. The main breakpoint of change in the fresh and dry masses of oat root was observed when the NaCl concentration of the medium changed from 200 mM to 300 mM, in the case of emmer - from 0 mM to 100 mM and from 200 mM to 300 mM. In the case of barley, the described breakpoint was observed during the change of medium NaCl concentration from 300 mM to 400 mM, and in the case of wheat - from 100 mM to 200 mM. The reduction of FM and DM of wheat, oat and emmer stem was steeper at low concentrations of NaCl, and milder - at high concentrations. In the case of change of NaCl concentration from 0 mM to 100 mM, the fresh and dry masses of the barley stem even increased by 3.8% and 0.6%, respectively, whereupon they decreased like for the rest of studied crops. At low concentrations of NaCl the fresh and dry masses of the emmer leaf decreased drastically along with the increase in salt concentration. When the concentration of NaCl changed from 0 mM to 100 mM, no significant change in FM and DM of leaves was observed in oat, while in wheat and barley they increased, thereafter, along with the increase in NaCl concentration, at first a significant decrease was observed, then the decrease became insignificant, and in some cases, the fresh and dry masses of leaves even increased by 3.1-5.1%.

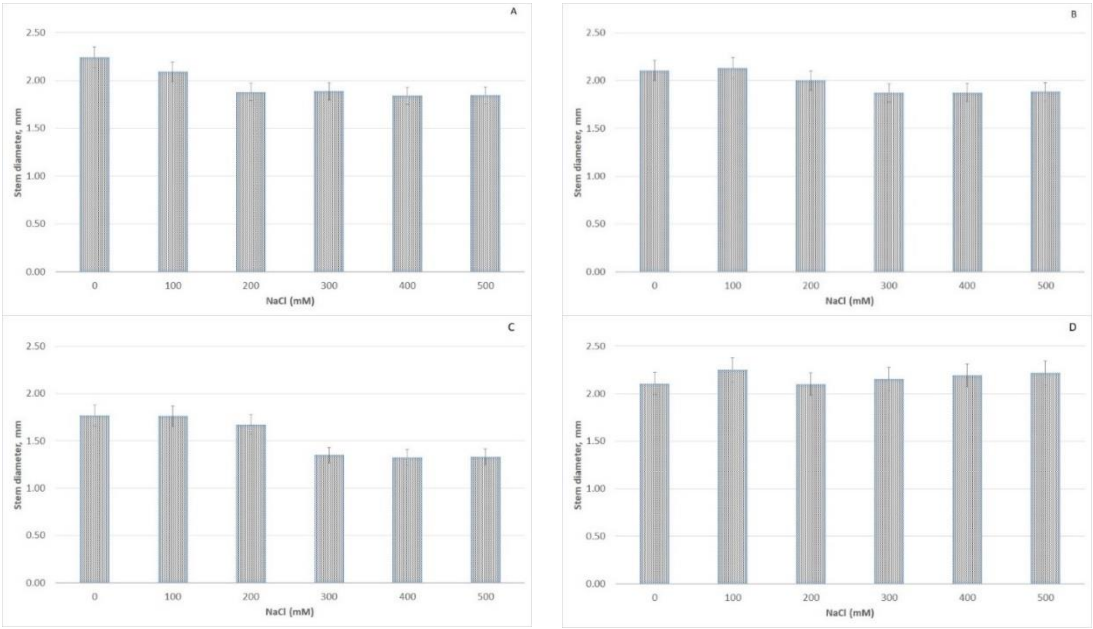

Figure 3. *Effect of NaCl stress on stem diameter of studied crops (A - wheat, B - oat, C - emmer, D - barley, n = 30)*

The change of FM_r/FM_s and DM_r/DM_s ratios in various crops proceeded in different ways (*Table 1*). With the increase in NaCl concentration, the FM_r/FM_s and DM_r/DM_s ratios in wheat and emmer generally increased. In wheat the increase occurred more evenly, and in emmer it was dramatic at low concentrations of NaCl. Along with the change in NaCl concentrations from 0 mM to 100 mM, the values of FM_r/FM_s and

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DM_r/DM_s in barley decreased, but later they increased along with the increase of salt concentration up to higher values. The change of mentioned ratios in oat along with the change in NaCl concentration was not significant.

Table 1. *Effect of NaCl stress on some growth parameters and tissue water content of studied crops (n = 30)*

Crops	NaCl (mM)	FM_{root}, g	DM_{root}, g	FM_{stem}, g	DM_{stem}, g	FM_{leaf}, g	DM_{leaf}, g	FM_r/FM_s	DM_r/DM_s	RWC%	SWC%	LWC%
Wheat	0	1.356	0.243	2.193	0.632	0.736	0.214	0.463	0.287	82.110	71.184	70.863
	100	1.232	0.222	1.761	0.509	0.759	0.225	0.489	0.303	81.975	71.114	70.346
	200	0.959	0.166	1.318	0.397	0.469	0.157	0.537	0.299	82.703	69.861	66.578
	300	0.767	0.156	0.859	0.266	0.457	0.163	0.583	0.364	79.609	68.996	64.266
	400	0.760	0.156	0.672	0.229	0.440	0.159	0.684	0.403	79.452	65.943	63.810
	500	0.768	0.160	0.676	0.231	0.445	0.171	0.686	0.400	79.111	65.860	61.587
Oat	0	1.290	0.171	2.912	0.673	0.591	0.133	0.368	0.213	86.715	76.888	77.493
	100	0.987	0.157	2.464	0.595	0.593	0.132	0.323	0.216	84.054	75.869	77.684
	200	0.893	0.140	1.800	0.452	0.476	0.135	0.392	0.239	84.324	74.899	71.664
	300	0.613	0.105	1.273	0.330	0.421	0.129	0.362	0.228	82.915	74.039	69.330
	400	0.575	0.103	1.260	0.326	0.401	0.133	0.346	0.223	82.174	74.114	66.845
	500	0.581	0.106	1.262	0.327	0.354	0.133	0.360	0.230	81.840	74.087	62.541
Emmer	0	1.859	0.232	3.033	0.616	0.815	0.182	0.483	0.291	87.519	79.709	77.608
	100	1.379	0.175	1.689	0.443	0.646	0.146	0.591	0.297	87.313	73.786	77.439
	200	1.355	0.168	1.264	0.343	0.589	0.135	0.731	0.351	87.598	72.871	77.093
	300	0.935	0.133	0.855	0.236	0.413	0.119	0.738	0.376	85.745	72.398	71.267
	400	0.899	0.129	0.806	0.218	0.417	0.120	0.735	0.382	85.655	72.920	71.340
	500	0.841	0.130	0.701	0.199	0.411	0.122	0.757	0.407	84.508	71.676	70.339
Barley	0	1.850	0.213	2.044	0.508	0.887	0.184	0.631	0.307	88.511	75.157	79.299
	100	1.331	0.187	2.121	0.511	0.923	0.175	0.437	0.273	85.949	75.899	81.080
	200	1.124	0.172	1.398	0.359	0.779	0.167	0.516	0.326	84.723	74.290	78.510
	300	1.114	0.169	0.968	0.249	0.574	0.136	0.722	0.438	84.843	74.277	76.258
	400	0.837	0.149	0.797	0.209	0.465	0.136	0.663	0.432	82.218	73.745	70.826
	500	0.767	0.147	0.729	0.205	0.459	0.140	0.646	0.427	80.813	71.899	69.573

Effect of NaCl stress on osmotic tolerance and water status of studied crops

For the assessment of osmotic tolerance abilities and water status of crops the following indices were determined: RWC%, SWC%, LWC%, REL, and LS.

In the current study, the RWC%, SWC% and LWC% values in studied crops decreased under conditions of treatment with increasing concentrations of NaCl (0-500 mM). From plants grown in 500 mM NaCl medium as compared to 0 mM NaCl, the greatest decrease in RWC% was observed in barley (8.70%), in SWC% - in emmer (10.08%), and in LWC% - in oat (19.29%), while relatively slight reduction in RWC% and LWC% was observed in emmer (3.44% and 9.37% respectively), and in SWC% - in oat (3.64%).

In general, the highest values of REL were observed in emmer, and the lowest - in barley (*Fig. 4*). Along with the increase in NaCl concentration in the range of 0-500 mM in the root medium of crops, the change in REL values proceeded differently. The value

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of REL increased the most in emmer, reaching 93.39 from 67.06, followed by wheat - from 57.38 to 82.68, and barley - from 29.86 to 50.11. The change of REL value in oat along with the increase in NaCl concentration (0-500 mM) was not significant.

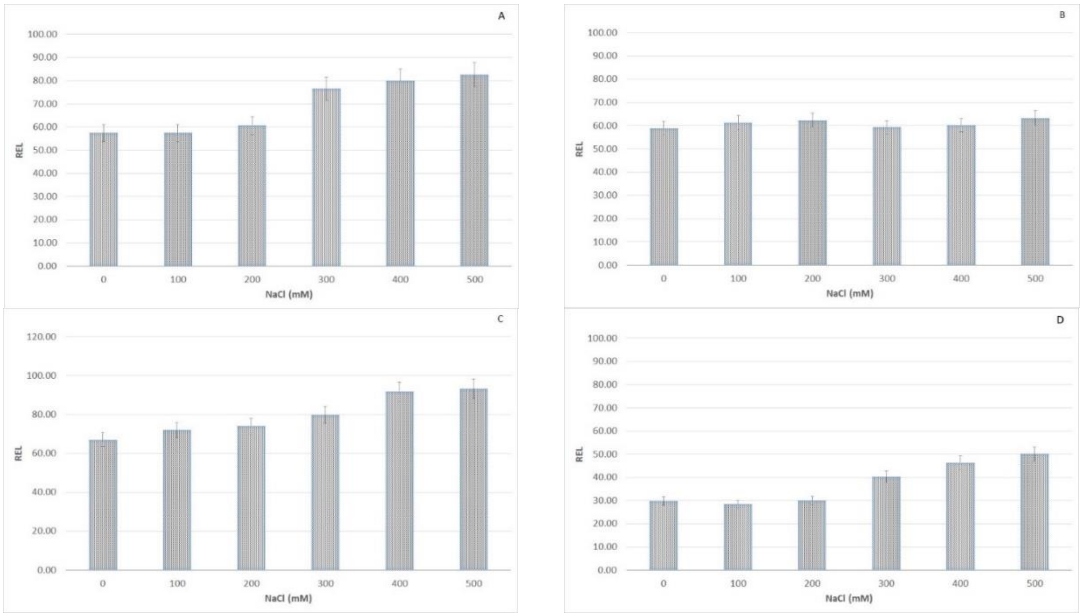

Figure 4. *Effect of NaCl stress on leaves REL of studied crops (A - wheat, B - oat, C - emmer, D - barley, n = 30)*

The results of the study of leaves succulence are presented in *Fig. 5*. LS changes in wheat and oat were not significant, while in emmer, along with the increase in NaCl concentration, it initially increased, reaching the highest value at 100 mM NaCl concentration, afterwards decreased, and in barley, in parallel with the increase in NaCl concentration, the value of LS significantly enhanced by 19.73% in plants grown in 500 mM NaCl medium as compared to 0 mM NaCl.

Effect of NaCl stress on chlorophyll content and gas exchange of studied crops

The results of the research of photosynthetic pigment of crops are presented in *Fig. 6*. The CCI values changed depending on both the change in NaCl content in the root medium and the growth stages of the crops. In other words, along with the growth of plants, depending on the change of vegetation stages (budding, flowering, earing, etc.), an increase or decrease in the value of CCI was observed in different crops. However, along with the increase in salinity degree, the value of CCI significantly decreased in all crops. From the measurements carried out 10 and 20 days after the completion of salt treatment, it was found out that from among plants grown in 500 mM NaCl medium as compared to those grown in 0 mM NaCl medium, the greatest decrease in CCI value was observed in oat (77.06% and 74.39%, respectively), and the least decrease - in barley (58.05% and 72.43%, respectively). And after 30 days of treatment, the greatest decrease was observed in emmer (79.35%), and the least - in wheat (72.78%). In some crops, an increase in the value of CCI was observed during the second measurement compared to the first (mainly at medium concentrations of NaCl). This indicated that crops were partially adapted to the influence of the stress factor during that period.

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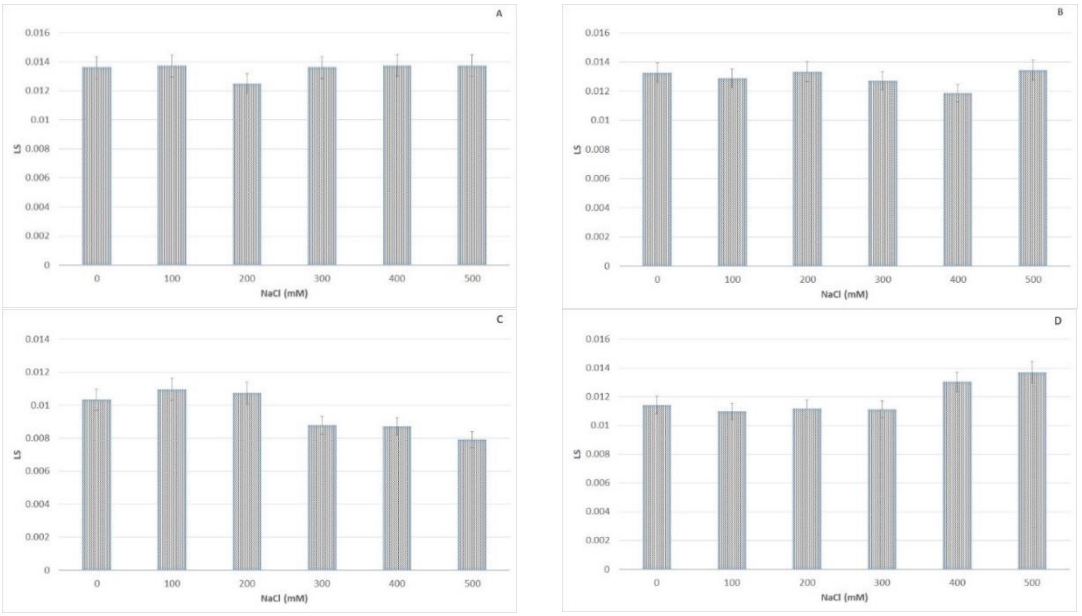

Figure 5. *Effect of NaCl stress on LS of studied crops (A - wheat, B - oat, C - emmer, D - barley, n = 30)*

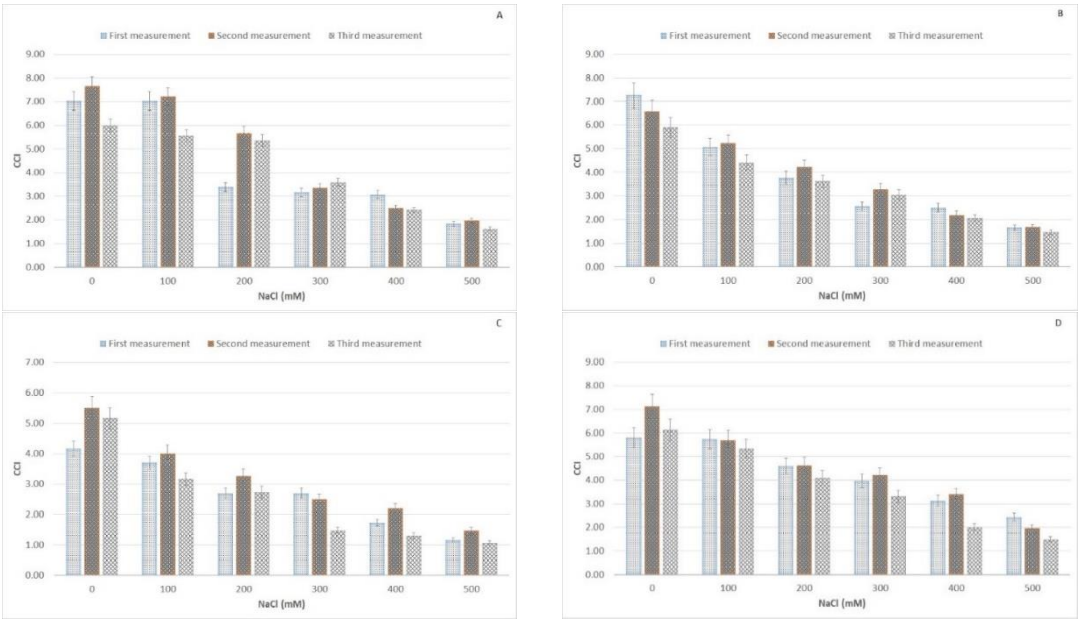

Figure 6. *Effect of NaCl stress on CCI of studied crops (A - wheat, B - oat, C - emmer, D - barley, n = 30)*

The results of the study of photosynthetic rate, transpiration rate and WUE under different conditions of salt treatment are presented in *Table 2*. In comparison with control, the greatest decrease in the value of P_n of crops grown under conditions of the maximum concentration of NaCl in the root medium was observed in the case of emmer, and the least - in the case of wheat. In all studied crops, the decrease in P_n value along with the increase in NaCl concentration did not proceed proportionally. In particular, in wheat and

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oat P_n did not undergo significant changes in the range of NaCl concentrations from 300 mM to 500 mM, whilst in barley it dropped sharply at NaCl concentrations from 0 mM to 100 mM (by 35.9%), but at higher concentrations of salt from 100 mM to 300 mM the decrease of P_n was small (from 100 mM to 200 mM - by 13.8%, and from 200 mM to 300 mM - by 10.9%). Transpiration rate decreased practically in all crops grown in 500 mM NaCl medium as compared to those grown in 0 mM NaCl medium, except the oat. The sharpest decrease was observed in wheat (91.38%), whilst in oat it increased almost 2 times. The changes in WUE along with the increase in NaCl concentration were different in various crops. In particular, it generally decreased in oat, but in wheat and emmer it increased in the beginning, afterwards decreased, whereas in barley the change was not significant. This indicates that different crops use water differently as a result of involvement of defense mechanisms.

Table 2. *Effect of NaCl stress on gas exchange of crops (n = 30)*

Salinity degree (NaCl, mM)	Wheat			Oat			Emmer			Barley		
	P_n	E	WUE	P_n	E	WUE	P_n	E	WUE	P_n	E	WUE
0	10.29	5.86	1.76	11.01	0.53	20.88	9.41	4.07	2.31	10.97	1.58	6.94
100	6.10	3.30	1.85	9.41	0.42	22.66	7.16	2.64	2.71	7.03	1.48	4.76
200	6.57	1.34	4.92	5.41	0.61	8.83	7.24	2.24	3.23	6.06	1.25	4.85
300	3.34	0.43	7.80	3.87	1.46	2.66	4.50	0.94	4.80	5.40	1.03	5.27
400	4.41	0.50	8.86	3.64	1.71	2.13	1.81	0.47	3.86	3.63	0.84	4.32
500	3.97	0.51	7.87	3.71	1.66	2.24	1.37	0.58	2.35	3.32	0.54	6.14

Effect of NaCl stress on ionic content of studied crops root, stem and leaf

The analysis of some ions and TDS of roots, stems and leaves of the studied crops is shown in *Table 3*. The accumulation of ions in the roots, stems and leaves of different crops along with the increase in NaCl concentration proceeded in different ways. In general, along with the increase of NaCl concentration in the root medium, the content of K^+ in the roots and stems of all crops first increased, then significantly decreased (especially in the roots of crops). From the comparative analysis of different crops, it was found out that in the roots of plants grown in 500 mM NaCl medium, compared to those grown in 0 mM NaCl, the decrease in K^+ content was more dramatic in barley (82.80%), and in the stems of plants - in emmer (41.69 %). The tendency of K^+ content decreasing also remained in emmer leaves, whilst in wheat, oat and barley leaves, on the contrary, along with the increase in NaCl concentration, an increase in K^+ content was mainly observed (at 500 mM NaCl concentration - in wheat and starting from 300 mM NaCl - in barley the content of K^+ decreased). The content of K^+ in leaves of plants grown in 500 mM NaCl medium compared to those grown in 0 mM NaCl enhanced more significantly in oat (79.11%). An increase in Na^+ and Cl^- contents was mainly observed in the roots, stems and leaves of crops along with the increase in NaCl concentration. Only in some cases (for example, in the roots of oat, emmer, and barley), at high NaCl concentrations, a certain decrease in Na^+ and Cl^- contents was observed, which was probably caused by the activation of crop defense mechanisms. Compared to control, the greatest increase in Na^+ content in roots was observed in emmer (in plants grown in 300 mM NaCl medium), in stems and leaves - in wheat (in plants grown in 500 mM NaCl medium).

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Table 3. *Effect of NaCl stress on ionic content of crops root, stem and leaf (mg/g, n = 3)*

Crops	Salinity degree (NaCl, mM)	K^+			Na^+			Ca^{2+}			Cl^-			TDS		
		root	stem	leaf	root	stem	leaf	root	stem	leaf	root	stem	leaf	root	stem	leaf
Wheat	0	3.41	14.80	9.36	7.67	0.81	1.48	3.63	0.25	2.92	0.02	0.02	0.02	24.8	28.8	35.4
	100	4.01	19.80	9.80	12.33	8.47	9.89	2.90	0.28	1.73	1.11	0.50	0.47	35.5	48.9	55.5
	200	3.99	20.00	9.89	18.04	10.80	12.92	3.57	0.32	1.25	3.63	3.95	3.75	43.4	55.5	56.8
	300	3.25	16.10	10.07	18.94	20.10	17.33	3.16	0.36	1.25	6.04	10.85	13.40	47.3	62.2	61.9
	400	2.77	14.60	11.45	18.70	23.20	19.05	3.34	0.40	1.23	10.15	14.50	14.60	47.6	75.6	64.7
	500	2.74	11.97	10.96	19.30	33.62	23.86	2.88	0.47	1.20	11.01	32.00	21.10	47.8	93.9	72.8
Oat	0	2.64	12.07	6.32	5.23	4.54	5.58	0.78	0.42	1.88	0.04	0.04	0.03	19.7	34.3	42.9
	100	5.45	13.50	6.34	15.50	20.95	23.00	0.94	0.41	1.56	0.45	0.84	3.12	39.7	67.7	63.4
	200	4.88	12.37	6.62	19.01	30.30	26.76	0.94	0.48	1.56	2.21	5.22	4.35	43.9	92.0	72.3
	300	3.49	11.60	8.77	19.92	38.10	28.66	0.62	0.60	1.25	7.15	13.50	15.30	47.8	106.1	94.0
	400	1.71	11.45	10.72	18.78	45.45	35.42	0.62	0.62	1.88	7.55	28.30	25.50	43.8	125.1	103.3
	500	1.41	11.05	11.32	18.35	46.78	39.85	0.62	0.61	1.72	7.52	44.60	36.10	41.7	141.3	125.1
Emmer	0	5.49	12.45	9.68	5.63	3.32	3.36	1.19	0.63	1.19	0.09	0.03	0.13	24.2	25.9	39.3
	100	4.97	14.63	5.61	16.98	19.72	8.48	1.28	0.42	0.94	1.20	0.56	1.46	39.7	57.4	44.8
	200	3.76	13.95	5.75	19.25	33.28	15.65	1.04	0.46	1.25	6.07	10.88	4.43	43.3	72.2	55.9
	300	2.85	9.76	4.55	21.64	62.28	27.14	1.23	0.61	1.28	9.55	36.00	20.10	50.6	119.1	74.8
	400	2.73	7.24	3.21	19.78	64.03	26.75	1.31	0.52	1.25	12.60	43.50	18.00	43.1	120.8	73.6
	500	2.31	7.26	3.31	18.58	65.20	27.32	1.25	0.63	1.37	10.54	53.30	17.40	40.0	122.7	73.4
Barley	0	3.72	12.23	11.45	7.50	4.08	4.08	1.09	0.40	1.75	0.05	0.04	0.03	24.9	28.9	44.1
	100	3.48	17.10	18.96	19.86	22.30	13.35	1.14	0.42	1.61	0.53	1.05	0.38	41.1	60.6	62.1
	200	2.04	14.70	19.22	24.00	34.13	18.85	1.08	0.49	1.50	6.25	13.50	4.16	40.4	67.8	71.6
	300	0.84	12.50	14.35	24.40	48.64	27.20	1.25	0.52	1.57	5.12	25.70	22.20	38.3	97.0	84.4
	400	0.65	10.15	14.85	23.80	61.51	32.90	1.21	0.63	1.50	5.34	56.00	27.40	37.1	117.1	96.6
	500	0.64	10.05	14.75	20.50	60.43	37.28	1.04	0.63	1.62	4.97	56.40	32.00	35.5	120.1	109.6

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While from among plants grown in 500 mM NaCl medium the greatest increase in Cl^- content was observed in root of wheat, in stems - in emmer, and in leaves - in oat. The change in Ca^{2+} content in the roots and leaves of crops along with the increase in NaCl concentration in the root medium was mostly not significant. In parallel with the increase in NaCl concentration, an increase in Ca^{2+} content was observed in stems of wheat, oat and barley, while the change in Ca^{2+} content in emmer was not significant. Along with the increase in NaCl concentration, a decrease in Ca^{2+} content in wheat leaves was observed, whereas the change was not significant in the rest of the crops.

The change of Na^+/K^+ ratio in the roots, stems and leaves of different crops in parallel with the increase in NaCl concentration in the root medium, proceeded differently. In particular, in comparison with control, in the roots of plants the increase in Na^+/K^+ ratio was greater in barley; in the stems of studied crops the increase was greater in wheat, and in the leaves - in emmer. It should be noted that in absolute values, the Na^+/K^+ ratio in the stem was the smallest in wheat, and the largest - in emmer.

Analysis of roots, stems and leaves of plants showed that along with the increase in NaCl concentration, an increase in the value of TDS was mainly observed. Only in oat, emmer, barley roots and in leaves of emmer, a certain decrease in TDS was observed in case of high NaCl concentrations in the root medium. Compared to 0 mM NaCl, the greatest increase of TDS in roots and leaves was observed in oat (1.43 times - in roots of plants grown in 300 mM NaCl medium and 1.92 times - in leaves of plants grown in 500 mM NaCl medium), while the greatest increase of TDS in stems was observed in emmer (3.74 times - in plants grown in 500 mM NaCl medium).

Phytodesalination capacity of studied crops

In roots, stems and leaves of crops harvested after 30 days of NaCl treatment, significantly higher accumulation of Na^+ and Cl^- was observed than in control plants (*Table 3*). From a phytodesalination viewpoint, the amount of Na^+ and Cl^- accumulated in the above-ground mass of plants is the most important. As a result of studies, it was found out that the greatest accumulation of Na^+ and Cl^- in the stems was observed in emmer and barley, and the accumulation of the mentioned ions in the leaves was greater in oat and barley (*Table 4*). In general, along with the increase in NaCl content in the root medium, the above-ground mass of all crops decreased, but the Na^+ and Cl^- content increased there. From the calculations it was found that oat has the highest phytodesalination capacity and wheat - the least.

Table 4. *The mass of Na^+ and Cl^- (mg) accumulated in the above-ground parts of the studied crops (per plant)*

Crops	Salinity degree (NaCl, mM)	Na^+	Cl^-	Crops	Salinity degree (NaCl, mM)	Na^+	Cl^-
Wheat	100	19.95	1.11	Emmer	100	37.05	1.59
	200	19.36	6.69		200	47.44	15.28
	300	21.87	12.89		300	59.65	35.52
	400	19.94	13.08		400	57.42	38.97
	500	28.22	26.49		500	51.13	40.82
Oat	100	65.31	3.91	Barley	100	54.12	2.41
	200	66.65	11.36		200	54.48	20.36
	300	57.95	22.23		300	53.86	30.41
	400	68.80	43.96		400	55.89	50.35
	500	72.05	68.07		500	51.68	47.66

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Discussion

Salinity, especially NaCl-induced stress, is a significant environmental threat interfering with the capacity of crops to reach their full genetic potential, as it induces a number of growth and developmental restrictions. Therefore, for the enhancement of crop productivity it is crucial to select salt-tolerant crops. Comparison between some grasses that have different tolerance to salinity is necessary in order to characterize the most pertinent physiological and molecular mechanisms responsible for such reaction (Rao et al., 2023) as well as to supply useful information concerning the distinguishing traits that can facilitate the finding of new genotypes tolerant to stress (Taïbi et al., 2016; Souana et al., 2020). Various studies related to salt-tolerance of wheat, oat, emmer and barley have been carried out by a number of scientists (Munns et al., 2016; Sapre et al., 2018; Aycan et al., 2021; Oubaidou et al., 2021). According to the results of numerous studies the salt tolerance of crops depends not only on genetic characteristics, but also on the environmental factors, the properties of growth medium, and various irrigation managements. Indications show that some environmental conditions such as humidity, temperature, intensity of light etc. significantly affect plant response to salt stress (Rodrigues et al., 2016; Arain et al., 2021). In order to make a more reliable assessment in this regard, it is very important to compare crops salt tolerance with each other under the same environmental conditions.

NaCl stress is a complicate physiological and multifactorial phenomenon characterized by a spectrum of stresses colaterally with various morphophysiological and biochemical changes (Srivastava et al., 2015). In the current study, the growth indicators, physiological and biochemical responses of some varieties of wheat, oat, emmer, and barley to NaCl-induced stress were investigated. We have also properly studied the ability of these crops to accumulate Na and Cl under conditions of different NaCl concentrations in the root media.

Growth parameters such as shoot length, stem diameter, FM and DM in different crops were changed in different ways along with the increase in concentrations of NaCl in the root medium. In all crops, in parallel with the increase in salinity, a reduction in plant height was observed, but after reaching the high concentrations of NaCl, the stabilization of the mentioned parameter was observed. It should be noted that the decline in height occurred more sharply in emmer and starting from 200 mM NaCl concentration did not undergo significant changes, whilst in wheat and barley the stabilization began from 300 mM NaCl concentration, and in oat - from 400 mM NaCl concentration. In other words, due to the various adaptation mechanisms activated in oat, the plant was able to maintain a certain growth even in the case of 300 mM NaCl concentration in the root medium, and from four studied crops, the least decrease in the growth in the medium of 500 mM NaCl compared to control was observed in oat. Similar results concerning growth inhibition under salt stress conditions have been stated in other glycophytic (salinity sensitive) crops (Taïbi et al., 2016; Souana et al., 2020). On the contrary, in some salt-tolerant plant species (*Pennisetum giganteum*, alfalfa), an increase in shoot length was observed along with the increase of salinity up to a certain critical level (Steppuhn et al., 2012; Hayat et al., 2020b).

Measurement of biomass accumulation under regulated conditions can allow the assessment of NaCl stress response along with tolerance and other life-supporting functions of plants (Gong et al., 2013). Furthermore, NaCl tolerance was commonly evaluated by comparing biomass loss under long-term saline against non-saline conditions (Li et al., 2022). Compared to plants grown in 0 mM NaCl medium, the

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maximal reduction of root, stem, leaf FM and DM in all studied crops grown in 500 mM NaCl medium (except the FM of root) was observed in emmer, and the least decrease was registered in wheat root and leaf FM, barley root DM, oat stem FM, DM, and leaf DM. These effects included decrease in various growth parameters of oat, wheat, barley and other crops, like the main responses to salt stress revealed by other researchers (Al-Karaki, 2001; Wang et al., 2001; Dang et al., 2008; Han et al., 2013, 2015; Ali et al., 2022; Zia-ur-Rehman et al., 2023). As in the case of shoot length, FM and DM also significantly decreased in emmer at 100 mM and 200 mM NaCl concentrations, whilst in some above-ground organs of the rest of crops, the increase of FM and DM was even observed at 100 mM NaCl concentration.

In different crops, the changes in RWC%, LWC%, SWC%, REL and LS under conditions of NaCl treatment were registered. Among studied crops grown in 500 mM NaCl medium in comparison with 0 mM NaCl, the most intensive dehydration of plant roots occurred in barley, of stems - in emmer, and of leaves - in oat. RWC%, SWC% and LWC% are the major indicators of plant metabolic activity and water status under conditions of abiotic stress (Ashraf et al., 2013). If plants are able to resist and to some extent to counteract the changes in these determinants, this indicates an effective redox homeostasis and osmotic regulation in leaves and roots of crops (Ellouzi et al., 2014). An intensive dehydration was observed in plant species less adapted to salinity, such as tomato plant (Tanveer et al., 2020), whereas halophyte plants, like *Frankenia pulverulenta* and *Atriplex prostrata* avoided dehydration of tissues (Bueno et al., 2020).

The extent of REL from plants (particularly sensitive to salinity rather than tolerant) tissues can be regarded as a factor in permeability changes of membrane and considered as a biomarker of stress (Ghorbani et al., 2019). The largest increase of REL in parallel to the increase in NaCl concentration was revealed in emmer, while this index did not undergo significant changes in oat. Tolerant plant species typically accumulate large amounts of organic solutes to neutralize the inhibitory influence of osmotic stress as a result of NaCl-induced tissue water content reduction and increase in REL (Ashraf et al., 2013; Al Murad et al., 2020). The change of LS was different in various crops, in particular, it decreased in emmer, increased in barley, and the change was not significant in the other two crops. The increase in leaf succulence (namely the content of water per unit area) is one of the main mechanisms (that supresses the transpiration) used by plants to react to a low external water potential caused by salinity (Ma et al., 2019). In addition, a decrease in water potential along with other salinity-related stresses is commonly associated with a number of effects in some glycophytic plants, including (1) a decrease in RWC%, (2) cellular dehydration, (3) a decline of osmotic potential, (4) reduced water uptake, and (5) loss of turgor, in this way affecting the growth and productivity of plants (Akçay et al., 2012; Chakraborty et al., 2012).

NaCl stress reduces the activity of photosynthesis by the decrease in chlorophyll content. The change in the level of photosynthetic pigments caused by salinity-induced oxidative stress (as a result of formation of reactive oxygen species) can be interpreted as an effective biochemical marker of plant tolerance to stress (Panda et al., 2019; Hayat et al., 2020b). The change in photosynthetic pigments in tolerant plant species is significantly less than in sensitive ones, even when they are treated with higher concentrations of NaCl (Shafeiee and Ehsanzadeh, 2019; Causin et al., 2020). The studies revealed that 30 days after the completion of the treatment with NaCl the least decrease in CCI value was observed in wheat in all experimental schemes compared to 0 mM NaCl in the root medium, followed by barley (under conditions of 100 mM, 200 mM and

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300 mM NaCl in the root medium) and oat (under conditions of 400 mM and 500 mM NaCl), whilst the greatest decrease in the value of CCI in all schemes of the experiment was observed in emmer. The intense reduction in contents of photosynthetic pigments was described both in halophytic and glycophytic plants as a result of NaCl-induced stress (Boriboonkaset et al., 2013; Amjad et al., 2015).

Photosynthetic activity is regarded as a significant indicator for the effective assessment of crop yield, persistance, and high responsivity to salt stress (Foyer, 2018). Photosynthetic capability decreases under conditions of salt stress specified by lower stomatal conductance and water supply as well as reduced photosynthetic pigments (Amjad et al., 2015; Baniasadi et al., 2018; Shoukat et al., 2023). Stomata counterbalance CO_2 intake by leaf for photosynthetic carbon increase with concomitant water loss (Hedrich and Shabala, 2018). Among the crops grown in 500 mM NaCl medium compared to 0 mM NaCl, the maximum decrease in photosynthetic rate was observed in emmer and the least - in wheat. A similar result was also recorded concerning the change of CCI values, which was also consistent with the results of studies implemented by other researchers (Shabala et al., 2005). The transpiration rate also decreased in almost all crops. Salinity and lower water potential stimulate the biosynthesis of leaf abscisic acid, which eventually signalizes for the closure of stomata and aids plants to exclude water loss under salinity stress (Hedrich and Shabala, 2018).

The accumulation of mineral elements in roots and shoots of plants is another important physiological mechanism of adaptation to salinity (Joshi et al., 2023; Singh et al., 2023). Homeostasis and regulation of ion transport is one of the key indicators of plant salinity tolerance (Isaenkov and Maathuis, 2019). Some halophytic monocotyledons and most glycophytes have tendency to restrict the transport of toxic ions, primarily of Na^+, to plant leaves, while halophytic dicotyledons tend to accumulate toxic ions in the shoots, that is a beneficial mechanism for increasing osmotic pressure and maintaining cell turgor in foliar tissues (Tejera et al., 2006; Al-Hassan et al., 2016b). The studied crops, using various physiological adaptation mechanisms, accumulated ions (Na^+, Cl^-, K^+ and Ca^{2+}) in their organs in different ways. Along with the increase in NaCl concentration in the root medium, the K^+ content in the roots and stems of all crops first increased, and then significantly decreased, except for emmer and barley roots, where the K^+ content decreased at once. And in the leaves (except for emmer) of plants under the salt treatment the content of K^+ increased, compared to plants grown in 0 mM NaCl medium. A high content of K in young growing tissues is related to salt tolerance in many plants (Larbi et al., 2020). The contents of Na^+ and Cl^- in the roots, stems and leaves of the studied crops mainly increased along with the increase in NaCl concentration in the root medium, which is known to impede the uptake of nutrients and exert influence upon the plant growth (Javaid et al., 2019). The Na^+/K^+ ratio is also very important from the point of view of activating the adaptation mechanisms of crops to salt stress. In the roots of plants grown in 500 mM NaCl medium in comparison with the plants grown in 0 mM NaCl medium, the mentioned ratio increased the least in wheat, whereas the Na^+/K^+ ratio in the stems and leaves increased the least in oat, followed by barley. Other researchers have also found an increase in the Na^+/K^+ ratio in crops, such as canola, maize, chickpea, wheat, barley, and lettuce along with the increase in salinity in the root medium (Kara and Keser, 2001; Tarakcioglu and Inal, 2002; Grewal, 2010). This increase in Na^+/K^+ ratio in plants with increasing NaCl concentration in soil may be conditioned by the competition of Na^+ with K^+ (Othman et al., 2023). This emulation can be at the level of absorption or transport or both. The results obtained in this study showed that the higher tolerance of crops could

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be interpreted by the comparatively less variation in Na^+/K^+ ratio and the availability of mechanisms limiting the transport of Na^+ from the roots of crops to the above-ground parts. This mechanism, which is more effective in salt-tolerant crops, minimizes the adverse impact of Na^+ accumulation in leaves, and ensures the less change in Na^+/K^+ ratio by reducing Na^+ and increasing K^+ transport from roots (Bayuelo-Jiménez et al., 2012; Assaha et al., 2017). Significant increase in Na^+ noted in the leaves of wheat, oat and barley under salinity stress was concomitant with the increase in K^+ concentrations, which indicated the activation of some physiological adaptation mechanisms. However, along with the increase in Na^+ content in the leaves of emmer, a decrease in K^+ concentration was observed there. Similar results were observed in bean, when plants exposed to salinity absorbed large amounts of Na^+ but lost high amounts of K^+ (Taïbi et al., 2016). Absorption of Na^+ causes depolarization of plasma membrane, initiating the activation of outward-directed K^+ channels, and consequently the loss of cellular K^+ (Ma et al., 2019). Higher Na^+ and K^+ accumulations were the characteristics of crops tolerant to salinity. The results of the present study prove that the capability to withstand salt stress is a function of ion accumulation and the capacity to uptake K^+ by roots and to transfer it to the leaves, as far as the differences in the content of K^+ are important in all instances.

The results of the correlation analysis of various chemical, growth and tissue tolerance indices of the studied crops and NaCl content in the root medium clearly showed that the NaCl content had a negative correlation with almost all growth and physiological parameters of crops. However, depending on the extent of resistance of the crops and the peculiarities of the involvement of defensive mechanisms, certain differences were observed. For example, cell membrane damage, determined by REL, as a result of the increase in NaCl content, changed the least in oat, leaf succulence increased the most in barley, and water use efficiency was the greatest in wheat.

Phytodesalination can be characterized as the phytoextraction of salts by the use of plants with ability to take up NaCl. Phytodesalination has been elaborated in recent years and has shown perspective results in various types of remediation projects such as the restoration of agricultural soils (Ravindran et al., 2007; Rabhi et al., 2010). Plants selected for phytosalination must be able to accumulate adequate amounts of Na^+ and Cl^- in their above-ground parts and tolerate elevated level of salinity (which can interfere with nutrition). The halophyte plants are able to accumulate large amounts of salts, but generally form small biomass. Some time ago, a debate arose among researchers about what was more essential for phytoremediation between hyperaccumulation of ions in shoots and high biomass of shoots (Ghazaryan et al., 2022). In this regard, not only the ability of plant to accumulate salts is very important, but also the formation of large above-ground biomass. In our study, substantial difference in uptake of ions was found out among the four crops. Oat has the greatest phytodesalination potential among the studied crops, and wheat - the least. Considering the fact that oat and barley compared to the other two crops, at high contents of NaCl in the root medium in general maintain their viability better, form large biomass and accumulate more Na^+ and Cl^- in their above-ground organs, they can be used for remediation and revegetation of salt-impacted agricultural soils.

Conclusions

Study results demonstrate different tolerance capability of wheat, oat, emmer and barley to endure increasing concentrations of NaCl in the root medium. There was

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significantly more adverse effect of rising level of root medium salinity on main growth attributes, REL, LS, CCI, photosynthetic rate, and transpiration rate of emmer compared with barley, oat, and wheat. The results of the present study prove that the ability to tolerate salt stress is a function of ion accumulation and the capacity to uptake K^+ by roots and transfer it to the leaves. Significant increase in Na^+ noted in the leaves of wheat, oat and barley under salinity stress was concomitant with the increase in K^+ concentrations, which indicated the activation of some physiological adaptation mechanisms. However, in the leaves of emmer, along with the increase in Na^+ content, a decrease in K^+ concentration was observed. Thus, emmer was impacted the most followed by wheat, oat, and barley at the highest level of root medium salinity. And since emmer is the most sensitive to salinity stress it will be impractical to grow it on salinized soils. Growing of comparatively tolerant species like oat and barley may be more appropriate and realistic; accordingly, they could be the better choice for saline agriculture. It should be mentioned that oat in addition to salt stress tolerance developed larger biomass and accumulated more Na^+ and Cl^- in shoots in comparison with the rest of studied crops, therefore it had the strongest phytodesalination capacity.

Considering the fact that barley and oat accumulate large amounts of ions in their above-ground parts and that they are viable and productive (with abundant biomass even when growing in highly saline environments), these plants could be assumed as promising tolerant and salt accumulating crops for further research in the field of sustainable crop production and concurrent phytodesalination.

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APPENDIX

Appendix 1. *Correlation among wheat growth response and related indices with changes in NaCl content in the root medium*

	Shoot length	**Stem diameter**	**FM_{root}**	**DM_{root}**	**FM_{stem}**	**DM_{stem}**	**FM_{leaf}**	**DM_{leaf}**	**RWC%**	**SWC%**	**LWC%**	**REL**	**LS**	**CCI**	**P_n**	**E**	**WUE**	**Na^+/K^+ (root)**	**Na^+/K^+ (stem)**	**Na^+/K^+ (leaf)**	**NaCl (mM)**
Shoot length	1.00																				
Stem diameter	0.97	1.00																			
FM_{root}	1.00	0.96	1.00																		
DM_{root}	0.98	0.98	0.98	1.00																	
FM_{stem}	0.99	0.95	0.99	0.95	1.00																
DM_{stem}	0.99	0.95	0.99	0.95	1.00	1.00															
FM_{leaf}	0.94	0.94	0.95	0.97	0.91	0.91	1.00														
DM_{leaf}	0.87	0.89	0.88	0.94	0.82	0.82	0.98	1.00													
RWC%	0.78	0.61	0.79	0.64	0.83	0.83	0.63	0.48	1.00												
SWC%	0.85	0.78	0.84	0.76	0.89	0.88	0.79	0.67	0.85	1.00											
LWC%	0.96	0.90	0.96	0.91	0.97	0.96	0.92	0.82	0.84	0.91	1.00										
REL	-0.89	-0.77	-0.90	-0.80	-0.93	-0.92	-0.80	-0.68	-0.97	-0.94	-0.95	1.00									
LS	-0.01	0.19	-0.01	0.19	-0.11	-0.11	0.23	0.38	-0.60	-0.28	-0.09	0.39	1.00								
CCI	0.87	0.76	0.86	0.76	0.91	0.90	0.75	0.61	0.94	0.97	0.94	-0.98	-0.40	1.00							
P_n	0.91	0.86	0.89	0.85	0.91	0.92	0.73	0.62	0.77	0.69	0.82	-0.80	-0.20	0.78	1.00						
E	0.98	0.99	0.97	0.97	0.96	0.96	0.90	0.84	0.67	0.75	0.90	-0.79	0.09	0.77	0.93	1.00					
WUE	-0.97	-0.89	-0.98	-0.93	-0.97	-0.97	-0.93	-0.86	-0.85	-0.90	-0.95	0.95	0.13	-0.90	-0.82	-0.90	1.00				
Na^+/K^+ (root)	-0.97	-0.92	-0.97	-0.92	-0.99	-0.99	-0.90	-0.80	-0.86	-0.94	-0.98	0.96	0.15	-0.95	-0.86	-0.92	0.97	1.00			
Na^+/K^+ (stem)	-0.81	-0.73	-0.80	-0.70	-0.85	-0.84	-0.70	-0.54	-0.87	-0.91	-0.92	0.92	0.34	-0.96	-0.75	-0.73	0.80	0.90	1.00		
Na^+/K^+ (leaf)	-0.95	-0.93	-0.93	-0.90	-0.96	-0.96	-0.83	-0.71	-0.77	-0.82	-0.94	0.86	0.08	-0.87	-0.94	-0.95	0.87	0.94	0.89	1.00	
NaCl (mM)	-0.94	-0.88	-0.93	-0.86	-0.96	-0.96	-0.85	-0.73	-0.86	-0.95	-0.98	0.95	0.20	-0.97	-0.84	-0.88	0.92	0.99	0.96	0.95	1.00

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Appendix 2. *Correlation among oat growth response and related indices with changes in NaCl content in the root medium*

	Shoot length	**Stem diameter**	**FM_{root}**	**DM_{root}**	**FM_{stem}**	**DM_{stem}**	**FM_{leaf}**	**DM_{leaf}**	**RWC%**	**SWC%**	**LWC%**	**REL**	**LS**	**CCI**	**P_n**	**E**	**WUE**	**Na^+/K^+ (root)**	**Na^+/K^+ (stem)**	**Na^+/K^+ (leaf)**	**NaCl (mM)**
Shoot length	1.00																				
Stem diameter	0.97	1.00																			
FM_{root}	0.97	0.91	1.00																		
DM_{root}	0.99	0.97	0.98	1.00																	
FM_{stem}	0.98	0.96	0.98	0.98	1.00																
DM_{stem}	0.99	0.97	0.98	0.99	1.00	1.00															
FM_{leaf}	0.98	0.96	0.92	0.95	0.96	0.96	1.00														
DM_{leaf}	0.27	0.37	0.37	0.41	0.30	0.31	0.20	1.00													
RWC%	0.91	0.81	0.97	0.92	0.92	0.91	0.86	0.30	1.00												
SWC%	0.97	0.93	0.98	0.97	1.00	0.99	0.93	0.32	0.93	1.00											
LWC%	0.96	0.92	0.88	0.91	0.91	0.92	0.99	0.12	0.85	0.88	1.00										
REL	-0.32	-0.15	-0.34	-0.22	-0.34	-0.32	-0.39	0.47	-0.47	-0.37	-0.46	1.00									
LS	0.36	0.37	0.43	0.44	0.37	0.37	0.22	0.29	0.40	0.36	0.15	0.43	1.00								
CCI	0.96	0.87	0.96	0.93	0.94	0.94	0.94	0.14	0.97	0.94	0.95	-0.53	0.30	1.00							
P_n	0.97	0.95	0.96	0.96	0.99	0.99	0.96	0.23	0.88	0.99	0.91	-0.37	0.33	0.93	1.00						
E	-0.94	-0.95	-0.89	-0.95	-0.88	-0.90	-0.92	-0.40	-0.84	-0.85	-0.91	0.10	-0.45	-0.87	-0.85	1.00					
WUE	0.97	0.99	0.91	0.96	0.97	0.97	0.97	0.24	0.80	0.94	0.93	-0.25	0.31	0.88	0.97	-0.90	1.00				
Na^+/K^+ (root)	-0.88	-0.81	-0.83	-0.84	-0.80	-0.81	-0.89	-0.07	-0.86	-0.77	-0.94	0.44	-0.28	-0.93	-0.78	0.90	-0.79	1.00			
Na^+/K^+ (stem)	-0.98	-0.92	-0.98	-0.97	-0.97	-0.97	-0.96	-0.22	-0.96	-0.97	-0.95	0.45	-0.35	-0.99	-0.96	0.90	-0.93	0.90	1.00		
Na^+/K^+ (leaf)	-0.53	-0.39	-0.66	-0.52	-0.63	-0.60	-0.48	0.04	-0.71	-0.69	-0.44	0.69	-0.13	-0.65	-0.64	0.25	-0.46	0.36	0.64	1.00	
NaCl (mM)	-0.97	-0.90	-0.94	-0.94	-0.93	-0.93	-0.97	-0.18	-0.94	-0.92	-0.98	0.48	-0.26	-0.99	-0.92	0.92	-0.90	0.96	0.98	0.54	1.00

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Appendix 3. *Correlation among emmer growth response and related indices with changes in NaCl content in the root medium*

	Shoot length	**Stem diameter**	**FM_{root}**	**DM_{root}**	**FM_{stem}**	**DM_{stem}**	**FM_{leaf}**	**DM_{leaf}**	**RWC%**	**SWC%**	**LWC%**	**REL**	**LS**	**CCI**	**P_n**	**E**	**WUE**	**Na^+/K^+ (root)**	**Na^+/K^+ (stem)**	**Na^+/K^+ (leaf)**	**NaCl (mM)**
Shoot length	1.00																				
Stem diameter	0.77	1.00																			
FM_{root}	0.93	0.92	1.00																		
DM_{root}	0.96	0.88	0.99	1.00																	
FM_{stem}	0.99	0.82	0.96	0.99	1.00																
DM_{stem}	0.97	0.90	0.98	0.99	0.98	1.00															
FM_{leaf}	0.93	0.93	0.99	0.99	0.97	0.99	1.00														
DM_{leaf}	0.98	0.83	0.96	0.99	0.99	0.98	0.97	1.00													
RWC%	0.67	0.92	0.86	0.79	0.72	0.81	0.84	0.70	1.00												
SWC%	0.96	0.66	0.89	0.93	0.97	0.91	0.88	0.95	0.59	1.00											
LWC%	0.72	0.99	0.90	0.85	0.78	0.87	0.91	0.78	0.96	0.62	1.00										
REL	-0.81	-0.91	-0.90	-0.86	-0.82	-0.88	-0.88	-0.79	-0.92	-0.69	-0.90	1.00									
LS	0.59	0.94	0.80	0.72	0.64	0.76	0.80	0.64	0.97	0.48	0.97	-0.88	1.00								
CCI	0.96	0.89	0.99	1.00	0.99	0.99	0.99	0.98	0.82	0.92	0.87	-0.88	0.76	1.00							
P_n	0.84	0.93	0.94	0.90	0.86	0.91	0.92	0.84	0.93	0.74	0.93	-0.99	0.89	0.92	1.00						
E	0.93	0.94	0.99	0.99	0.96	0.99	0.99	0.96	0.85	0.86	0.91	-0.92	0.81	0.99	0.95	1.00					
WUE	-0.47	-0.53	-0.51	-0.56	-0.52	-0.53	-0.58	-0.61	-0.21	-0.44	-0.45	0.21	-0.28	-0.51	-0.30	-0.53	1.00				
Na^+/K^+ (root)	-0.94	-0.93	-0.98	-0.98	-0.97	-0.99	-0.99	-0.96	-0.84	-0.88	-0.90	0.88	-0.81	-0.99	-0.91	-0.98	0.54	1.00			
Na^+/K^+ (stem)	-0.81	-0.98	-0.93	-0.89	-0.84	-0.91	-0.93	-0.83	-0.94	-0.69	-0.97	0.98	-0.93	-0.91	-0.99	-0.95	0.39	0.92	1.00		
Na^+/K^+ (leaf)	-0.83	-0.97	-0.94	-0.90	-0.85	-0.92	-0.94	-0.85	-0.93	-0.71	-0.96	0.98	-0.91	-0.92	-0.99	-0.96	0.40	0.93	1.00	1.00	
NaCl (mM)	-0.88	-0.92	-0.94	-0.91	-0.89	-0.94	-0.93	-0.87	-0.92	-0.79	-0.92	0.97	-0.88	-0.94	-0.97	-0.95	0.28	0.95	0.97	0.97	1.00

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Appendix 4. *Correlation among barley growth response and related indices with changes in NaCl content in the root medium*

	Shoot length	**Stem diameter**	**FM_{root}**	**DM_{root}**	**FM_{stem}**	**DM_{stem}**	**FM_{leaf}**	**DM_{leaf}**	**RWC%**	**SWC%**	**LWC%**	**REL**	**LS**	**CCI**	**P_n**	**E**	**WUE**	**Na^+/K^+ (root)**	**Na^+/K^+ (stem)**	**Na^+/K^+ (leaf)**	**NaCl (mM)**
Shoot length	1.00																				
Stem diameter	-0.13	1.00																			
FM_{root}	0.90	-0.44	1.00																		
DM_{root}	0.93	-0.40	0.99	1.00																	
FM_{stem}	0.99	-0.11	0.87	0.91	1.00																
DM_{stem}	0.99	-0.14	0.87	0.92	1.00	1.00															
FM_{leaf}	0.94	-0.22	0.84	0.89	0.98	0.98	1.00														
DM_{leaf}	0.95	-0.29	0.85	0.88	0.95	0.96	0.96	1.00													
RWC%	0.87	-0.47	0.97	0.98	0.87	0.87	0.87	0.82	1.00												
SWC%	0.80	-0.13	0.75	0.78	0.86	0.84	0.85	0.71	0.85	1.00											
LWC%	0.83	-0.28	0.78	0.84	0.90	0.89	0.95	0.83	0.88	0.91	1.00										
REL	-0.85	0.35	-0.79	-0.84	-0.91	-0.91	-0.97	-0.90	-0.87	-0.88	-0.98	1.00									
LS	-0.60	0.37	-0.66	-0.71	-0.70	-0.69	-0.79	-0.61	-0.81	-0.86	-0.94	0.88	1.00								
CCI	0.95	-0.34	0.94	0.97	0.96	0.96	0.96	0.92	0.97	0.88	0.93	-0.94	-0.80	1.00							
P_n	0.90	-0.48	1.00	0.99	0.86	0.87	0.84	0.87	0.96	0.72	0.78	-0.80	-0.64	0.94	1.00						
E	0.91	-0.35	0.90	0.93	0.94	0.94	0.95	0.89	0.95	0.93	0.95	-0.96	-0.84	0.98	0.90	1.00					
WUE	0.36	-0.33	0.54	0.50	0.24	0.27	0.19	0.35	0.36	-0.13	0.05	-0.05	0.08	0.31	0.56	0.15	1.00				
Na^+/K^+ (root)	-0.95	0.29	-0.86	-0.91	-0.96	-0.97	-0.98	-0.99	-0.86	-0.76	-0.90	0.94	0.71	-0.95	-0.88	-0.92	-0.34	1.00			
Na^+/K^+ (stem)	-0.93	0.37	-0.92	-0.95	-0.95	-0.95	-0.97	-0.94	-0.95	-0.84	-0.95	0.96	0.82	-0.99	-0.92	-0.97	-0.32	0.97	1.00		
Na^+/K^+ (leaf)	-0.94	0.38	-0.90	-0.93	-0.96	-0.96	-0.98	-0.96	-0.92	-0.85	-0.93	0.97	0.78	-0.98	-0.91	-0.98	-0.24	0.97	0.98	1.00	
NaCl (mM)	-0.93	0.38	-0.94	-0.96	-0.95	-0.95	-0.95	-0.92	-0.97	-0.89	-0.93	0.94	0.80	-1.00	-0.94	-0.99	-0.27	0.94	0.98	0.98	1.00

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