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Enhancement of Drought Resistance in Wheat and Corn by Nanoparticles of Natural Mineral Analcite

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Abstract. The effect of the application of nanoparticles of analcite to soil (at 0, 500, 1000 and 1500 mg L^{-1}) on drought resistance of wheat and corn seedlings was studied in pot experiments. The dependence of the analcite effect on soil moisture level and type was also evaluated. For this, three levels of soil moisture were modeled: 20%, 40% and 60% field capacity. The following types of soils were studied: greenhouse soil mixtures, gray podzolic and sandy soils. The positive effect has been established for all doses of analcite tested: seed germination, seedlings growth criteria as well as content of photosynthetic pigments increased, while characteristics of water balance less deviated from the norm under water deficit. Application of analcite caused sharp accumulation of protective antioxidants (flavonoids, carotenoids) and activation of catalase (in corn) under soil drought. While proline content decreased. The dependence of analcite effect on its dose, soil moisture level and type as well as species of tested plants was discussed.

Key words: bioactive silicon, analcite, nanoparticles, drought resistance, seedlings, *Triticum aestivum, Zea mays*

Introduction

Recent studies have shown an important role of silicon in the plant life. Silicon is widely present in plants in amounts equivalent to or higher than phosphorus and magnesium (NISHIMURA *et al.*, 1989). This element is fairly common in nature. However, continued exploitation of agricultural lands, along with the use of mineral fertilizers led to leaching of natural silicates from the soil. Today concentration of bioactive silicon in the soil is recognized to be a factor limiting the performance of crops especially such as rice and sugar cane (MA *et al.*, 2006).

The positive effect of bioactive silicon on plants is widely regarded in the scientific literature (EPSTEIN, 2001). Exogenous application of bioactive silicon was shown to promote growth and productivity of crops and to improve the quality of agricultural products. This is due primarily to improved mechanical properties of plant tissues, enhancement of systemic resistance to abiotic and biotic stress factors and the impact of Si on the uptake of N, P, K and Mo by plants (KOZLOV, 2007).

Analcite $[AlSi_2O_6]$-H_2O is a natural mineral of volcanic tuffs. It was shown to have marked positive effect on the functional state of living organisms. The inclusion of analcite to fertilizer promote root development, improves soil agro-physical characteristics by increasing moisture level and creating chemical depot for macro- and micronutrients (ZAIMENKO, 2008).

Despite many recent reports describing benefits of application of silicon containing minerals in ecological agriculture, the physiological mechanisms of their effects on crops remained undefined and controversial up till now. This prevents wide implementation of silicon in agriculture.

Therefore, the present investigation was undertaken to study the impact of analcite on drought resistance in wheat and corn seedlings depending on the dose of the mineral, soil type and moisture level.

Wheat is considered the first strategic food crop in Ukraine. It is the basic staple food for bread making. Corn is also one of the key grain crops with growing popularity in this region. In Ukraine wheat and corn crops are sometimes exposed to drought at various stages of growth. However the most vulnerable to drought these crops are at seedling stage.

Material and Methods

Seed materials. Wheat (*Triticum aestivum* L., cv. "Pereyaslavka") and corn (*Zea mays* L., hybrid "Titan"), which represented C_3 and C_4 types of fixation of carbon during photosynthesis, respectively, were used in this study.

Analcite application. Analcite nanoparticles (with size of 100 micron) were added to soil at 0, 500, 1000 and 1500 mg L^{-1} just before sowing seeds**.**

Soil types and moisture levels. Three types of soil were used: (**1**) greenhouse soil mixture consisting of compost, peat, leaf soil and sand (1:1:1:1), (**2**) gray podzol and (**3**) sand + Hellriegel nutrient solution. Soil were sieved through a 2 mm sieve and sterilized in an oven at 100 ^{o}C. Moisture level was maintained by gravimetric method at 20%, 40% and 60% field capacity (FC). Corn and wheat were cultivated for 21 and 28 days, respectively, at 22-30 °C temperature, natural sunlight level and 60-75% relative humidity.

Measurements. Success of adaptation of corn and wheat seedlings to water deficit was assessed by characteristics of growth and development (% of germinated seeds, dry weight of shoots and roots), water balance (relative water content and water deficit in the foliar tissues, transpiration rate), content of photosynthetic pigments, as well as content of protective biomolecules (proline, flavonoids) and catalase activity. Percentage of germinated seeds was counted on 3-5 days after sowing. The transpiration rate was determined by registering changes in weight of cut transpirating leaves for short time intervals (TRETYAKOV, 1990). Relative water content and water deficit were measured by gravimetric method (GRYGORYUK *et al*., 2003). Proline was extracted from freshly cut leaves by 3% sulfosalicylic acid. Its quantitative content was determined using qualitative reaction with ninhydrin on spectrophotometer "Spekol 11" (Carlzeiss / Jena, Germany) (STATSENKO & BUTYLKIN, 1999). Photosynthetic pigments were extracted from leaves by dimethylsulfoxide. Their quantitative content was determined using spectrophotometer "Spekol 11" (HISCOX & ISRAELSTAM, 1979). Catalase activity was determined by the method of PLESHKOV (1985). Flavonoids were extracted with 70% ethanol, their quantitative content was determined spectrophotometrically using qualitative reaction with $AlCl_3$ (KOMAROVA *et al*., 1998). The results presented in the tables are the means of four replications. The data were statistically analyzed using the least significant difference (LSD) test ($p<0.05$). The effect of analcite dose, soil type, moisture level, and species of tested plants on their adaption to soil drought was assessed using analysis of variance (ANOVA) and correlation analysis with the help of Statistica 6.0 software.

Results and Discussion

Seed germination

Under moderate and especially low soil moisture seed germination of wheat and corn noticeably decreased. Supplying of analcite nanoparticles to substrate promoted seed germination of corn and wheat (Table 1). The effect size, as a rule, positively correlated (correlation coefficient $R=0.21$, $p<0.05$) with the dose of the mineral and inversely with soil moisture level ($R=-0.49$, $p<0.05$). The stimulation observed on wheat seeds was more pronounced as compared to corn seeds under low soil moisture conditions. At 60% FC the opposite tendency was observed. No significant correlation between the degree of analcite protective effect and soil type was observed.

Growth parameters

In treatments with limited soil moisture, the growth of shoots of wheat and corn seedlings was markedly suppressed as compared to seedlings grown on substrate moistened to 60% FC (Table 2). The development of root system showed the opposite tendency for wheat grown on soils one and two and corn grown on soil 1. On the sandy substrate moistened to 20% FC, the growth of the root system of wheat and corn seedlings was also significantly depressed. The shoot/root ratio was generally lower in seedlings grown under limited soil moisture. This is a typical morphological adaptation of plants to water deficit in the soil.

Supplying of analcite nanoparticles to the soil increased phytomass accumulation by wheat and corn seedlings. For wheat, the increments in dry weight of shoots often were highly significant in comparison with plants grown without analcite. While the promoting effect of analcite on root phytomass was significant only in wheat seedlings grown on sandy substrate. For corn, both shoot and root dry weights were highly enhanced by analcite application in all treatments. Plant growth is an integral indicator of their vitality. Therefore, observed improvement of shoots and roots phytomass accumulation evidenced the restoration of basic life functions in wheat and corn seedlings under soil drought and the further amelioration of seedlings vigor under optimal soil moisture conditions (60% FC). The size of analcite effect on phytomass criteria positively correlated with its dose ($R=0.29$, $p<0.05$), soil fertility ($R=0.12$, $p<0.05$) and inversely – with soil moisture level ($R=-0.67$, $p<0.05$). The growth of corn seedlings was more pronouncedly stimulated by analcite application as compared to wheat.

Table 1. Wheat and corn seed germination (%) depending on analcite dose, soil type and moisture level. LSD – least significant difference at $P<0.05$

Plant species		Wheat			Corn		
Soil moisture, % FC	Analcite dose, mg L^{-1}	Soil 1	Soil 2	Sand	Soil 1	Soil 2	Sand
20	0	30.0	75.0	67.5	57.5	42.2	55.4
20	500	62.5	92.5	80.0	65.0	55.6	69.8
20	1000	80.0	97.5	90.0	65.0	57.8	74.0
20	1500	87.5	95.0	92.5	74.0	64.5	75.0
LSD		*1.63*	*1.22*	*1.87*	*0.99*	*0.71*	*0.70*
40	0	75.0	85.0	87.5	67.5	58.4	63.5
40	500	77.5	95.0	90.0	75.0	72.1	65.0
40	1000	82.5	92.5	97.5	80.0	79.5	72.7
40	1500	85.0	97.5	96.7	85.0	84.3	80.0
LSD		*2.42*	*1.51*	*1.66*	*0.97*	*0.66*	*0.98*
60	0	82.5	92.5	92.0	77.5	72.3	75.5
60	500	85.0	93.5	95.0	79.0	76.5	80.0
60	1000	82.5	95.0	98.0	87.5	85.0	86.8
60	1500	88.0	93.5	97.5	92.5	88.4	90.0
LSD		*2.41*	*1.02*	*1.57*	*1.11*	*0.57*	*0.52*

Table 2. Mean dry weight per plant of wheat and corn seedlings (mg) depending on analcite dose, soil type and moisture level. LSD – least significant difference at P<0.05

Soil moisture % FC	Analcite dose, mg L^{-1}	Soil 1			Soil 2			Sand		
		Roots	Shoots	Shoot/ root	Roots	Shoots	Shoot/ root	Roots	Shoots	Shoot/ Root
Wheat										
20	0	5.4	3.2	0.6	5.6	2.3	0.4	10.6	10.0	1.1
20	500	5.3	4.3	0.8	5.6	2.6	0.5	25.5	13.6	1.9
20	1000	5.5	7.8	1.4	5.8	2.9	0.5	24.7	12.9	1.9
20	1500	5.6	7.1	1.3	5.5	6.0	1.1	27.7	13.8	2.0
LSD		*0.5*	*0.5*	*0.4*	*0.4*	*0.6*	*0.4*	*0.8*	*0.7*	*0.5*
40	0	4.0	10.4	2.6	3.6	13.8	3.8	17.7	15.6	1.1
40	500	4.0	10.9	2.8	3.5	14.5	4.2	29.0	16.5	1.8
40	1000	3.8	13.5	3.6	3.4	17.4	5.1	28.7	16.3	1.8
40	1500	3.9	12.8	3.3	3.3	17.4	5.3	29.6	18.0	1.6
LSD		*0.4*	*0.7*	*0.4*	*0.5*	*0.6*	*0.5*	*0.4*	*0.5*	*0.3*
60	0	3.7	20.3	5.5	3.4	17.9	5.2	19.0	18.3	1.0
60	500	3.6	20.0	5.6	3.9	25.2	6.5	28.6	19.2	1.5
60	1000	3.7	20.8	5.6	3.9	25.3	6.4	33.7	18.6	1.8
60	1500	4.0	21.1	5.3	4.0	24.7	6.2	32.8	19.2	1.7
LSD		*0.7*	*0.4*	*0.3*	*0.2*	*0.6*	*0.2*	*0.9*	*0.5*	*0.5*
Corn										
20	0	65.5	23.6	0.4	44.2	13.3	0.3	26.7	13.3	0.5
20	500	70.8	38.0	0.5	55.6	27,2	0.5	41.4	28.6	0.7
20	1000	90.9	36.6	0.4	54.8	29.0	0.5	39.4	32.5	0.8
20	1500	83.3	38.5	0.5	55.5	27.5	0.5	33.1	38.8	1.2
LSD		*1.3*	*0.8*	*0.8*	*0.9*	*1.5*	*1.0*	*0.7*	*0.5*	*0.4*
40	0	47.4	21.1	0.4	38.6	21.4	0.6	63.3	32.2	0.5
40	500	49.4	29.4	0.6	55.5	35.5	0.6	109.3	49.3	0.5
40	1000	49.4	32.7	0.7	52.5	35.8	0.7	83.5	48.0	0.6
40	1500	50.9	39.5	0.8	68.6	33.9	0.5	80.5	49.5	0.6
LSD		*0.3*	*0.6*	*0.3*	*0.4*	*1.2*	*0.5*	*0.9*	*1.0*	*0.8*
60	0	42.4	35.2	0.8	89.0	44.0	0.5	60.6	41.9	0.5
60	500	45.4	40.0	0.9	93.9	48.3	0.5	96.3	43.7	0.5
60	1000	51.4	40.5	0.8	104.5	92.7	0.9	90.5	55.8	0.6
60	1500	52.9	46.2	0.9	96.3	89.6	0.9	107.5	70.0	0.7
LSD		*0.7*	*0.8*	*0.6*	*0.5*	*2.2*	*0.6*	*0.5*	*0.5*	*0.5*

Water balance

Under water deficit significant dehydration of foliar tissues was observed in seedlings of wheat and corn (Table 3). Application of analcite led to normalization of water metabolism under water deficit. At 60% FC some reduction of water deficit and increase in transpiration rate (statistically not significant) in leaves of plants treated with analcite were observed. This evidenced amelioration of water balance and gas exchange processes in wheat and corn at all levels of soil moisture by analcite application. The effect size positively correlated with the dose of the mineral and soil fertility ($R=0.16$ and $R=0.12$, respectively, $p<0.05$) and inversely – with soil moisture level ($R=-0.26$, $p<0.05$).

Table 3. Characteristics of water balance in leaves of wheat and corn seedlings depending on analcite dose, soil type and moisture level. LSD – least significant difference at P<0.05. WC – relative water content (%), WD – water deficit (%), TR – transpiration rate (mg/cm²·h).

Soil moisture % FC	Analcite dose, mg L^{-1}	Soil 1			Soil 2			Sand		
		WC	WD	TR	WC	WD	TR	WC	WD	TR
					Wheat					
20	0	58.2	74.0	1.22	70.7	64.0	0.42	72.2	31.0	0.90
20	500	78.5	43.1	1.82	82.6	57.2	0.63	88.6	21.7	1.34
20	1000	79.2	30.7	2.71	84.7	44.0	0.80	88.8	10.1	1.33
20	1500	81.6	37.5	3.10	87.0	40.4	1.22	89.2	6.5	1.46
LSD		*5.3*	*4.2*	*0.41*	*3.7*	*2.4*	*0.19*	*1.8*	*2.9*	*0.29*
40	0	80.7	14.8	1.60	87.2	13.4	2.39	85.0	15.1	0.96
40	500	91.2	10.7	1.96	91.5	6.5	2.45	91.8	10.6	1.87
40	1000	90.0	9.0	2.54	92.1	4.0	3.20	91.7	10.7	2.11
40	1500	91.6	8.1	3.37	92.5	4.4	3.78	93.1	7.0	2.12
LSD		*1.8*	*2.8*	*0.37*	*2.0*	*2.4*	*0.35*	*2.7*	*1.4*	*0.13*
60	0	90.9	7.0	2.39	93.6	11.3	3.83	90.8	3.9	3.12
60	500	91.5	5.1	3.00	92.2	5.0	4.04	92.7	1.8	3.30
60	1000	91.2	4.5	3.67	92.6	3.8	4.68	92.4	1.9	3.31
60	1500	91.7	2.2	3.85	93.6	2.2	4.63	92.5	1.5	3.25
LSD		*2.1*	*2.4*	*0.66*	*4.1*	*3.9*	*0.85*	*1.4*	*2.0*	*0.14*
					Corn					
20	0	77.4	61.1	0.48	58.5	80.7	0.85	74.9	49.0	0.67
20	500	82.4	41.0	0.66	76.7	67.5	1.02	88.9	28.0	0.88
20	1000	84.6	39.4	0.61	79.6	71.9	1.14	90.0	19.9	0.98
20	1500	85.2	31.4	0.69	77.1	65.3	1.17	90.2	13.6	1.05
LSD		*1.7*	*2.3*	*0.23*	*2.9*	*3.3*	*0.34*	*1.9*	*3.8*	*0.26*
40	0	85.2	29.8	0.81	87.1	17.8	1.10	87.3	30.8	0.97
40	500	89.6	25.2	0.89	91.7	9.7	1.34	91.3	19.6	1.12
40	1000	90.8	19.2	1.09	92.7	5.7	1.41	91.6	16.6	1.24
40	1500	91.0	17.8	1.09	93.5	3.8	1.55	92.5	10..8	1.22
LSD		*3.9*	*1.6*	*0.21*	*2.6*	*5.2*	*0.33*	*1.9*	*2..4*	*0.24*
60	0	91.2	13.8	1.78	91.9	16.6	2.35	89.6	18.0	1.97
60	500	92.1	4.1	1.71	92.0	10.6	2.45	92.3	14.0	2.02
60	1000	92.3	3.8	1.91	92.7	6.0	2.59	92.5	8.2	2.13
60	1500	92.7	2.5	1.91	92.4	6.1	2.88	93.4	7.0	2.14
LSD		*2.9*	*1.9*	*0.4*	*1.4*	*0.1*	*0.48*	*3.1*	*2.5*	*0.27*

Photosynthetic pigments

Photosynthesis is the main metabolic process that provides biomass accumulation in plants. Its rate depends on the content of photosynthetic pigments in foliar tissues, their composition and ratio. The results of the analysis of the content of chlorophylls a and b as well as carotenoids are shown in Table 4. Under soil drought a significant decrease in the content of photosynthetic pigments (chlorophylls a and b, carotenoids) and the chlorophyll a to chlorophyll b ratio in leaves of wheat and corn seedlings was observed.

Analcite application led to a sharp increase in content of photosynthetic pigments (chlorophylls a, b and carotenoids) and chlorophyll a/b ratio. No statistically significant correlation between the size of analcite effect with its dose and soil fertility was found. While inverse correlations between the size of analcite effect and soil moisture ($R=-0.31$, $p<0.05$) was established.

Thus, the application of analcite nanoparticles to substrate promoted induction of synthesis of photosynthetic pigments in leaf tissues of wheat and corn or modified ways of biosynthesis of photosynthetic pigments in the direction of enhancement of drought resistance of plants. Increase of chlorophyll a/b ratio in photosystems indicated the reducing of stress. An important role of carotenoids in the biosynthesis of ABA and maintaining the viability of plants under stressful conditions has been described in the scientific literature (MALUF *et al*., 1997). It is also known that carotenoids are components of the antioxidant systems involved in protecting membranes from damaging effects of free radicals produced during water stress (PINZINO *et al*., 1999). Since photosynthetic pigments are highly vulnerable to the oxidative stress, a significant increase in carotenoid content in case of analcite application to substrate is very important to protect the photosynthetic system and maintaining its operation under soil drought.

Proline content

Accumulation of proline in plant cells facilitates storage of water and is an important physiological mechanism of plant adaptation to drought (KUZNETSOV & SHEVYAKOVA, 1999). In treatments with limited soil moisture the proline content noticeably increased (Table 5).

Analcite application to the soil led to reduction of proline content in leaves of wheat and corn seedlings in all treatments. This indicated a lower stress level in seedlings treated with analcite and pointed to the fact that accumulation of proline is not related to the manifestation of the protective action of analcite. There was not found any statistically significant correlation between the size of analcite effect with its dose and soil type and moisture level.

Catalase activity

Activation of catalase in response to stress is a key process in the development of defense reactions in plant cells. Catalase breaks down hydrogen peroxide to oxygen and water, thus preventing its toxic effect to plant organism (WILLEKENS, 1997).

Application of analcite nanoparticles to the substrate resulted in the opposite effect on catalase activity in leaves of wheat and corn grown under soil drought. In the first case, the activity of catalase decreased proportionally to analcite dose, in the second - grew. At 60% FC application of analcite to a substrate led to reduction of catalase activity in corn leaves while in wheat it did not changed. This evidenced the greater sensitivity of corn catalase to analcite application as compared to wheat. No statistically significant correlation between the size of the analcite effect with its dose, soil fertility and moisture level was revealed.

The content of flavonoids

The content of flavonoids in the leaves of corn and wheat seedlings parabolically depended on the level of soil moisture, with a maximum at 40% FC. This was the evidence of the involvement of flavonoids in the responses of the tested plants to water deficit in the soil. The lowest level of flavonoids in leaf tissues of wheat and corn was observed at 20% FC. (Table 7). Under such soil moisture conditions analcite application stimulated accumulation of flavonoids in the leaves of wheat and corn seedlings. This pointed to activation of the corresponding defensive antioxidant system in response to drought stress by analcite nanoparticles. In treatments moistened to 40% and 60% FC analcite application led to the reduction of flavonoid content in leaves. This reaction pointed to the lower stress level in plants treated with analcite.

Table 4. The content of photosynthetic pigments (mg·g^{-1}) dry weight in leaves of wheat and corn depending on analcite dose, soil type and moisture level. LSD-least significant difference at P<0.05

Soil moisture %FC	Analcite dose, mg L^{-1}	Soil 1			Soil 2			Sand		
		Chl a	Chl b	Car	Chl a	Chl b	Car	Chl a	Chl b	Car
Wheat										
20	0	2.7	1.6	1.3	5.5	4.1	1.0	5.8	3.2	3.0
20	500	6.3	2.7	2.4	9.0	5.3	1.8	7.7	3.9	4.0
20	1000	6.9	2.7	2.4	10.3	4.7	3.1	8.6	3.6	3.7
20	1500	13.0	5.2	5.9	10.5	3.9	3.3	8.4	3.8	3.9
LSD		*1.3*	*0.5*	*0.3*	*0.4*	*0.5*	*0.2*	*1.4*	*0.4*	*0.4*
40	0	16.3	10.8	7.6	11.4	5.8	3.8	12.3	6.7	4.2
40	500	18.4	10.4	7.4	12.1	6.0	4.6	15.7	5.9	5.6
40	1000	17.5	8.3	7.5	14.3	6.5	5.2	13.6	5.5	5.9
40	1500	17.3	8.3	8.2	15.4	6.2	5.0	15.2	5.5	5.9
LSD		*0.8*	*0.7*	*0.8*	*1.1*	*0.5*	*0.1*	*1.1*	*0.3*	*0.6*
60	0	17.0	7.2	8.2	15.0	5.2	4.0	11.6	5.5	4.8
60	500	20.9	10.5	9.7	14.8	5.1	4.0	13.3	4.8	4.5
60	1000	19.9	10.3	8.1	16.6	5.5	4.8	12.9	4.2	4.5
60	1500	19.1	7.6	8.8	16.5	5.8	4.5	13.5	4.8	5.3
LSD		*1.2*	*0.7*	*0.3*	*0.5*	*0.5*	*0.8*	*1.2*	*0.6*	*0.3*
Corn										
20	0	4.5	3.4	2.0	2.6	1.9	1.2	4.2	2.9	1.9
20	500	6.5	5.6	3.2	7.5	4.5	1.8	7.0	3.6	2.1
20	1000	6.0	4.9	4.1	7.2	4.6	2.7	8.9	4.0	3.0
20	1500	6.4	4.6	4.8	7.8	4.9	2.5	9.0	3.8	2.8
LSD		*0.7*	*0.1*	*0.3*	*1.2*	*1.2*	*0.2*	*1.2*	*1.2*	*0.4*
40	0	12.7	6.2	5.6	9.1	4.6	2.1	9.0	5.5	3.0
40	500	17.1	6.0	3.7	10.4	4.4	2.1	12.9	6.1	3.4
40	1000	16.9	5.4	3.8	11.0	3.6	2.6	10.9	4.7	4.3
40	1500	18.0	6.0	3.9	11.7	3.7	3.0	11.6	4.6	4.1
LSD		*1.2*	*0.3*	*0.1*	*1.1*	*1.1*	*0.3*	*2.1*	*2.3*	*0.7*
60	0	11.2	6.2	4.2	13.6	5.1	2.5	11.8	4.3	3.3
60	500	12.8	8.0	3.8	15.0	5.0	2.8	14.1	4.5	3.4
60	1000	13.6	8.7	3.6	16.8	5.7	3.2	11.6	4.3	3.9
60	1500	13.5	7.2	4.2	19.5	6.6	2.9	19.9	5.1	5.0
LSD		*0.5*	*0.2*	0.5	*1.1*	*1.3*	*0.2*	*3.1*	*1.3*	*0.7*

Table 5. Proline content (mg per g of dry weight) in the shoots of wheat and corn depending on analcite dose, soil type and moisture level. LSD-least significant difference at P<0.05

Plant species		Wheat			Corn		
Soil moisture % FC	Analcite dose, mg L^{-1}	Soil 1	Soil 2	Sand	Soil 1	Soil 2	Sand
20	0	8.1	11.2	4.3	3.2	4.5	2.5
20	500	7.3	10.4	4.1	3.3	3.8	1.8
20	1000	4.1	8.1	3.0	2.3	2.5	1.7
20	1500	3.8	6.3	2.3	2.0	2.4	1.7
LSD		*0.4*	*0.5*	*0.3*	*0.3*	*0.4*	*0.4*
40	0	2.6	6.2	2.7	2.1	3.0	1.5
40	500	1.5	5.7	2.8	2.5	2.1	1.3
40	1000	0.9	5.1	2.3	1.5	2.0	1.5
40	1500	1.2	4.4	2.6	0.4	2.3	0.9
LSD		*0.5*	*0.6*	*0.3*	*0.6*	*0.6*	*0.5*
60	0	2.8	3.4	3.2	1.4	2.9	1.9
60	500	2.2	2.8	3.1	1.0	1.1	1.4
60	1000	1.0	2.4	3.0	0.6	1.6	1.6
60	1500	1.4	1.7	3.0	0.9	1.3	1.2
LSD		*0.4*	*0.4*	*0.4*	*0.4*	*0.5*	*0.5*

Table 6. Catalase activity (mmol H_2O_2/min per 1 g of dry weight) in the leaves of wheat and corn depending on analcite dose, soil type and moisture level. LSD-least significant difference at P<0.05

Plant species		Wheat			Corn		
Soil moisture % FC	Analcite dose, mg L^{-1}	Soil 1	Soil 2	Sand	Soil 1	Soil 2	Sand
20	0	36.46	30.95	8.75	6.15	4.43	4.48
20	500	35.42	14.70	6.17	6.68	3.30	4.41
20	1000	24.28	13.90	5.97	7.89	5.65	4.75
20	1500	22.31	12.01	4.38	7.89	8.47	7.23
LSD		*2.4*	*2.7*	*3.1*	*1.8*	2.9	2.4
40	0	20.71	18.75	7.71	10.67	8.44	3.54
40	500	20.71	16.78	6.99	8.87	4.81	3.06
40	1000	20.71	16.78	5.42	14.21	10.84	3.63
40	1500	20.71	12.17	4.50	19.54	10.86	4.21
LSD		*3.1*	*2.7*	*1.6*	*2.2*	*1.9*	*3.2*
60	0	10.83	7.08	5.66	8.98	7.22	3.03
60	500	11.91	6.69	5.66	9.66	9.02	2.68
60	1000	11.91	6.53	5.66	9.66	9.00	1.61
60	1500	11.91	6.04	5.66	7.70	6.19	1.52
LSD		*2.0*	*3.0*	*2.4*	*1.6*	*1.8*	*1.7*

Table 7. The content of flavonoids (mg per 1 g dry weight) in the leaves of wheat and corn depending on analcite dose, soil type and moisture level.
LSD-least significant difference at P<0.05

Plant species		Wheat			Corn		
Soil moisture, % FC	Analcite dose, mg L^{-1}	Soil 1	Soil 2	Sand	Soil 1	Soil 2	Sand
20	0	1.46	0.52	3.23	1.55	1.67	1.43
20	500	3.54	1.91	4.35	1.65	7.62	1.65
20	1000	3.97	1.72	6.91	4.49	5.83	1.85
20	1500	6.71	3.29	5.14	4.57	7.16	3.11
LSD		*0.9*	*1.1*	*1.3*	*1.1*	*1.0*	*1.1*
40	0	7.33	3.71	5.92	5.90	9.29	2.48
40	500	7.10	2.41	4.02	2.43	4.75	2.19
40	1000	5.99	1.86	3.99	5.92	5.20	1.98
40	1500	5.94	1.81	3.50	5.26	3.92	1.62
LSD		*1.1*	*1.1*	*0.8*	*1.1*	*1.2*	*1.2*
60	0	6.74	1.26	6.86	3.05	5.83	2.01
60	500	5.07	1.16	4.97	3.44	5.76	1.91
60	1000	5.67	1.68	4.10	3.02	5.08	1.28
60	1500	4.84	1.13	4.54	2.55	5.04	1.26
LSD		*0.8*	*0.8*	*1.0*	*1.1*	*1.1*	*1.0*

No statistically significant correlation between the size of analcite effect with its dose and soil fertility was revealed. However the size of analcite effect inversely correlated ($R=-0.26$; $p<0.05$) with the soil moisture level.

Conclusions

The data presented indicate that the application of nanoparticles of analcite to substrate contributes to the increase in the resistance of corn and wheat plants to drought stress: seed germination, seedlings growth criteria as well as content of photosynthetic pigments increased, while characteristics of water balance less deviated from the norm under water deficit. Analcite application induced a sharp accumulation of protective antioxidants (flavonoids, carotenoids) and activation of catalase (in corn) under soil drought, while accumulation of proline was not related to the manifestation of the protective action of analcite. Analcite is also known to improve water regime of the soil by alteration of agrophysical soil characteristics (ZAIMENKO, 2008).

The effect size of analcite, as a rule, positively correlated with its dose, soil fertility and inversely – with soil moisture level. It also varied depending on species of plants tested. For seed germination and water balance it was greater for wheat, while characteristics of content of photosynthetic pigments, biomass accumulation, catalase activity were more sensitive to analcite application in corn. This was the evidence of the differences in the development of protective responses to drought in wheat and corn.

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