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APPLICATION OF SILICEOUS MINERAL ANALCITE FOR OPTIMIZING THE PHYSIOLOGICAL, BIOCHEMICAL, ALLELOPATHIC, AND MICROBIOLOGICAL PROPERTIES OF PLANT-SOIL SYSTEM

Introduction. *The global climate change has caused uneven rainfall that impairs the hydro-physical properties of the soil and disrupts the microbiological processes. As a result, allelopathic soil sickness may occur.*

Problem Statement. *The search for and implementation of new effective and safe techniques to regulate the physiological, biochemical, allelopathic, and microbiological state of the plant-soil system are an urgent need in unstable ecological conditions.*

Purpose. *The purpose of this research is to optimize the physiological, biochemical, allelopathic, and microbiological properties of the plant-soil system under conditions of moisture deficiency and soil sickness, with the use of siliceous mineral analcite.*

Materials and Methods. *The effect of siliceous mineral analcite at a concentration of 0, 100, 200, and 300 mg per 200 ml soil substrate on the growth, moisture water regime of wheat and maize plants in model vegetation experiments under different moisture conditions (20%, 40% and 60% of full moisture capacity) and soil substrate type has been studied. In the field experiment, analcite is applied at a rate of 50 kg/ha before planting sugar beet seeds. The redox conditions, the content of phenolic compounds, and soil microbiological parameters in model and field experiments have been analyzed.*

Results. *The use of analcite has been established to optimize the growth, moisture regime of plants, as well as the allelopathic properties of the plant-soil system by reducing the content of free phenols, activating the development of microbial coenoses and redox processes. No phytotoxic manifestation of analcite has been noted.*

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Conclusion. *The application of analcite to improve the physiological, biochemical, allelopathic, and microbiological properties of the plant-soil system has been proposed. The prospects for the use of this mineral to improve the adaptability of plants in conditions of drought and soil sickness have been outlined.*

Keywords: winter wheat, maize, sugar beet, analcite, microbiocenosis, allelochemicals, moisture supply, and soil sickness.

Recently, humanity has been suffering from global climate change that results in disturbing the hydrothermal regime, reducing plant productivity, and accelerating the spread of pests and diseases.

Against the background of the global climate change, the problem of soil fatigue requires special attention. After all, the changes in the soil hydro-physical properties affect the concentration of organic compounds that may act as allelopathic compound in the soil solution [1]. In some cases, the soil fatigue is associated with the accumulation of allelopathically active compounds that either directly affect the plant growth or, through weakening the immune system, contribute to the spread of diseases, pests, etc. [1, 2]. The direct source of allelopathically active compounds may be both the in-life plant secretions and the post-harvest remains, dead organs, or related microbial groups. Organic compounds of a specific nature, which are synthesized by higher plants or microorganisms, are not immediately consumed in the phytocenosis and have the ability to accumulate. The accumulation of such compounds in soil with a high content of organic matter leads to the development of a specific microbiota adaptable to their decomposition. In the soils with a low humus content, where the heterotrophic cycle does not cover all alternative ways of decomposition of organic matter, they may accumulate in significant quantities [1]. Thus, in the soil, there take place the biological processes that are essential for plant nutrition and growth and their chemical interaction.

The monitoring studies in agroecosystems usually involve the determination of agrophysical and agrochemical indicators of soil fertility. However, they are not enough to objectively assess the state of the plant-soil system and to solve environmental problems. The ecological situation today requires the search for new approaches to assessing the state and dynamics of the soil environment with the involvement of biological indicators. They are more sensitive, adequately describe the physiological and sanitary condition of the plant-soil system, and may serve as indicators of the existence of the system in a certain period of time [3, 4].

Wheat, maize, and sugar beet are among the leading crops of agricultural production throughout the world, including Ukraine. These plants are able to accumulate allelopathically active compounds that may have autotoxic effects in the root environment [5, 6]. It is known that the negative effects of allelopathically active compounds may be exacerbated under adverse environmental conditions, in particular soil drought that is an often cause of water deficiency in plant tissues [7].

In order to find effective measures for solving these problems, the researchers have focused their attention on silicon-containing minerals of the zeolite group, the use of which has become widespread in various fields of science and technology due to their unique properties and multi-vector spectrum [8]. In particular, the silicon-containing mineral analcite from the group of zeolites of the silicate class (aqueous aluminosilicate) has proven itself to be a promising material for deactivating toxic substances and improving the physicochemical and hydrophysical properties of soil [8—11]. At the present stage, it is also obvious that silicon compounds have an important physiological role not only for higher plants, but also for the activity of microorganisms that are sensitive to any changes in environment conditions [12—15].

In view of the above, it should be noted that the development of new effective and safe technologies to increase productivity and adaptability of plants to the stress factors, such as drought and accumulation of phytotoxins of vegetable and microbial origin is extremely important today.

The purpose of this research is to optimize the physiological, biochemical, allelopathic, and microbiological properties of the plant-soil system under conditions of insufficient moisture supply and soil fatigue, with the use of silicon-containing mineral analcite.

To achieve this goal, it is planned to solve the following tasks:

- to evaluate the effect of silicon-containing mineral analcite on the physiological state of wheat and maize plants under different moisture conditions;
- to find out the role of analcite in the regulation of redox processes in the conditions of soil drought;
- to analyze the dynamic changes in the allelopathic characteristics of the plant-soil system with the use of silicon-containing mineral in the case of insufficient moisture supply;
- to study the effect of analcite on the microbiological properties of the plant-soil system;
- to describe the biochemical and allelopathic properties of the plant-soil system under the action of analcite.

Influence of analcite on the physiological, biochemical, and allelopathic properties of the plant-soil system under different moisture conditions

The effect of application of analcite (at a concentration of 0, 100, 200, and 300 mg per 200 ml soil substrate) on the growth, moisture regime of wheat (*Triticum aestivum L.*, *Pereyaslavka* variety) and maize (*Zea mays L.,* hybrid Titanium 220 SV), as well as on the biochemical and allelopathic properties of the root environment under different moisture conditions (20, 40, and 60% of total soil moisture (TSM)) and soil substrate type has been studied in model vegetation experiments. Greenhouse soil mix of humus, leaf soil, peat, and sand in the ratio 1: 1: 1: 1 (soil type No. 1), gray podzolic soil (soil type No. 2), and sand + solution of macronutrients according to Helrigel (soil type No.3) are used as a substrate for growing plants. All the soil substrates are sieved through a 2 mm sieve and sterilized in an oven at a temperature of 100 °C. The plants are grown under laboratory conditions: at a temperature of 22—30 °C, under daylight conditions (14 h day/10 h night), and a relative moisture of 60—75%. The experiments last 21 days.

On the 14th and 20th days after sowing of the test plants, the indicators of moisture regime of leaves (relative turgidity (%), deficit of relative turgidity, water deficit, and water retention capacity) have been determined by the weight method [16, 17]. At the end of the experiment, the test plants are removed from soil, dried at a temperature of 24—26 °C and the mass of the dry matter of aboveground parts (stems + leaves) and roots is measured.

The allelopathic soil analysis has been made by the direct biotesting method, with the growth of watercress roots (*Lepidium sativum* L.) used as biotest [18]. The phenolic substances are isolated from the soil by ion exchange (desorption) with the use of ion exchanger KU-2-8 (H^+) as a model of the root system with dissolving and absorbing ability in relation to mobile organic compounds [18]. The redox potential (RP) is determined in a suspension that simulates the soil solution at a soil-to-distilled water ratio of 1:1 by the potentiometric method [19, 20].

The statistical analysis of the results has been made by the ANOVA method (factor ANOVA) with the help of *Statistica 10.0* software package (*StatSoft* Inc., Tulsa, USA, 2011). Values of p less than 0.05 are considered statistically significant.

Reducing the moisture content in soil from 60% of TSM to 40% of TSM and especially to 20% of TSM significantly suppressed the physiological processes in the wheat and maize plants (Figs. 1—2) on all types of soil substrate. In particular, in the wheat plants grown on different types of substrate, at a soil moisture content of 40% of TSM, the relative turgidity and the water retention capacity of the leaves decrease by 31—45%

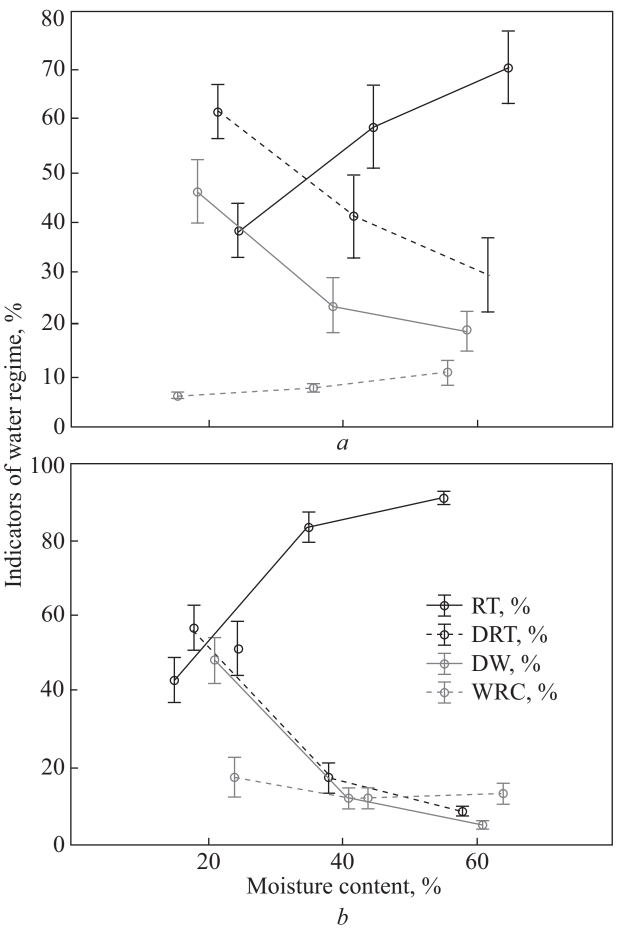


Fig. 1. Effect of the substrate moisture on the moisture regime the in leaves of test plants of maize (*a*) and wheat (*b*). RT is relative turgidity, DRT is deficit of relative turgidity, DW is deficit of water, WRC is water retention capacity. The points on the graphs are weighted average values. The vertical bars are confidence interval, $P_{0,05}$

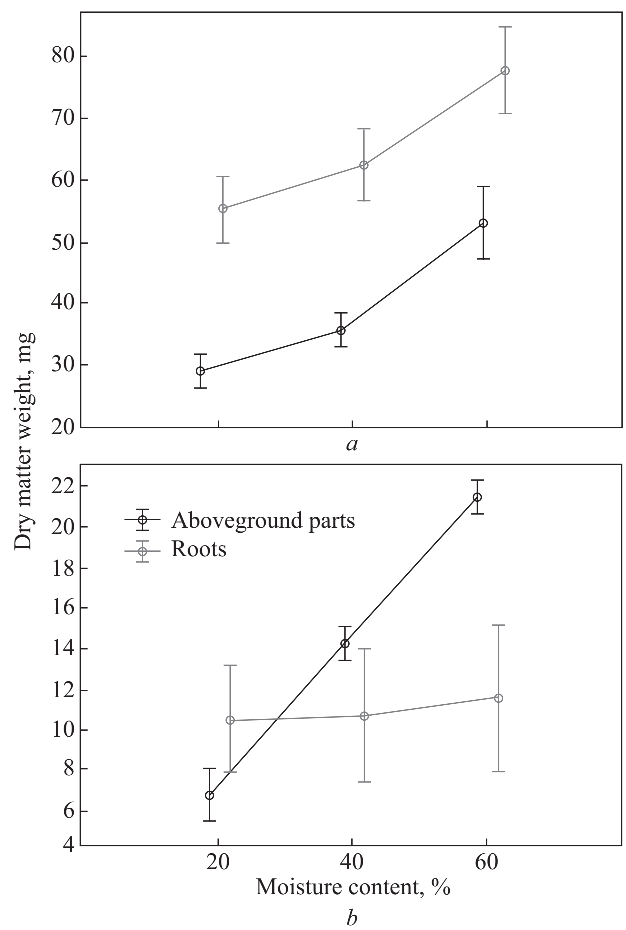


Fig. 2. Effect of the moisture on the dry matter weight of the test plants of maize (*a*) and wheat (*b*). The points on the graphs are weighted average values. The vertical bars are confidence interval, $P_{0,05}$

and 28—42%, respectively, while the water deficit and the relative turgidity deficit increase 2—2.5 times. The maize plants have been found to be more resistant. At a moisture content of 40% of TSM, the relative turgidity of maize leaves decreases by 26—32%, while the water deficit and the deficit of relative turgidity increase 1.7—4 times (depending on the type of substrate).

Deteriorating moisture regime inhibits the growth and accumulation of phytomass of the test plants. The most significant inhibitory effect has been reported for the mass of shoots (stems + leaves) of the test plants. In particular, the reduction of moisture content from 60 to 40% of TSM inhibits the accumulation of biomass by aboveground shoots (hereinafter, the average values for different soil types are given) by 33 and 28% for wheat and maize, respectively. At the same time, the corresponding indicators of the root phytomass decrease by only 20 and 7% for wheat and maize, respectively. At the minimum moisture, the mass of aboveground shoots of wheat and maize decreases more than twice, while the inhibition of root system growth is 29 and 10%, for wheat and maize, respectively.

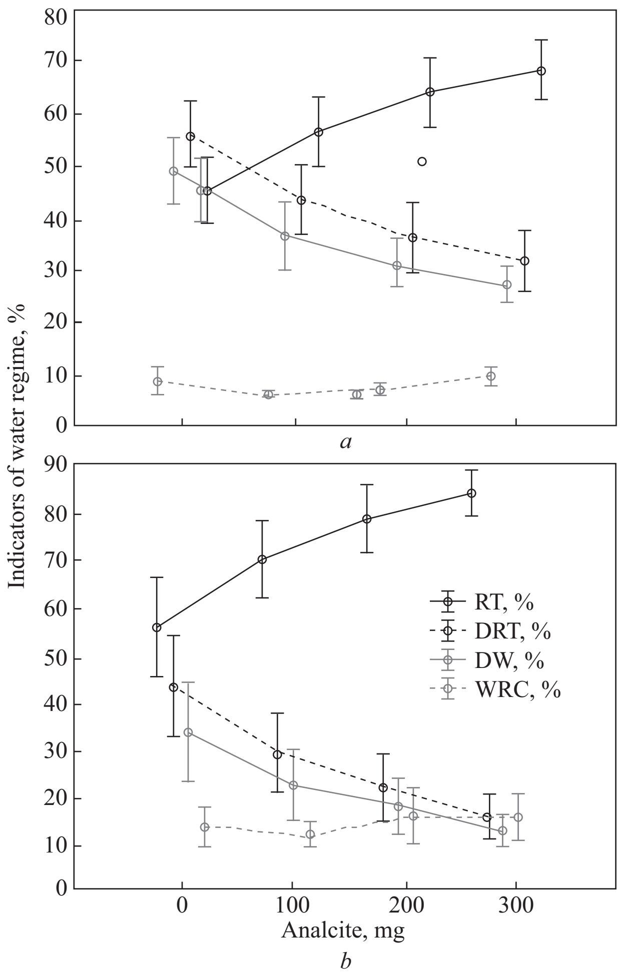


Fig. 3. Effect of analcite concentration (0, 100, 200, 300 mg / 200 ml soil substrate) on the moisture regime in leaves of the test plants of maize (*a*) and wheat (*b*). RT is relative turgidity, DRT is deficit of relative turgidity, DW is deficit of water, WRC is water retention capacity. The points on the graphs are weighted average values. The vertical bars are confidence interval, $P_{0,05}$

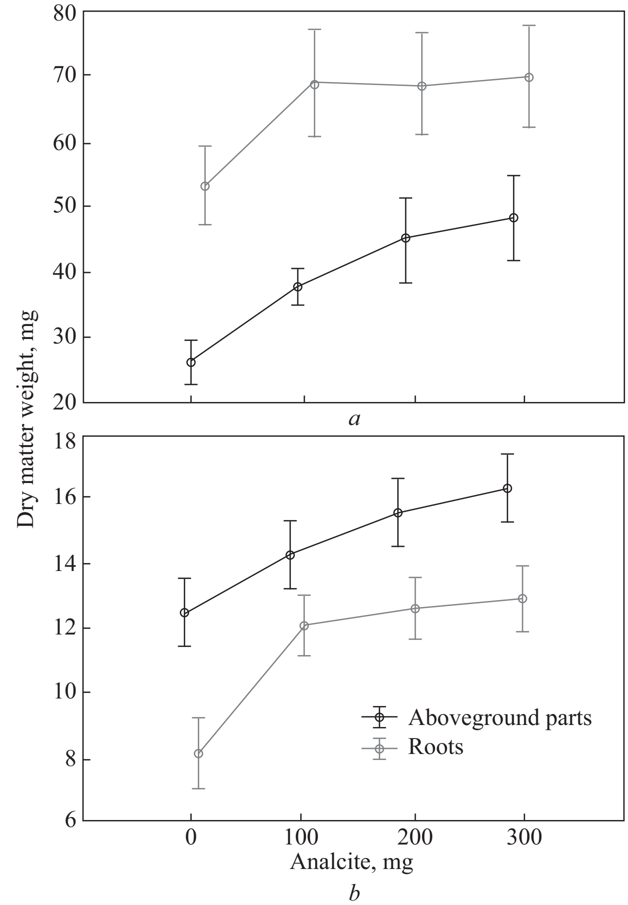


Fig. 4. Effect of analcite concentration (0, 100, 200, 300 mg / 200 ml soil substrate) on the dry matter weight of the test plants of maize (*a*) and wheat (*b*). The points on the graphs are weighted average values. The vertical bars are confidence interval, $P_{0,05}$

In general, wheat is more sensitive to soil drought than maize. The analysis of the influence of soil conditions on the sensitivity of wheat and maize to the moisture content has shown that the most vulnerable to drought are the plants grown on soil type No.3, while the most resistant are the test plants cultivated on soil type No. 1. In particular, the growth inhibition on soil type No. 3 is 68% for wheat and 62% for maize (the aboveground shoots); 45% for wheat and 56% for maize (the roots). At the same time, for the test plants on soil type No.1, the inhibition of the aboveground shoot growth is 44 and 49%, that of the root growth is 8 and 19%, for maize and wheat, respectively.

The application of analcite in all studied concentrations in the soil substrates has been established to contribute to improving the growth rates (dry mass of the aboveground parts (stems + leaves) and the roots) and normalizing the water metabolism (increasing relative turgidity, water retention capacity of leaves, decreasing water deficit and deficit of relative turgidity) in all variants of the experiment (Figs. 3—4). The protective effect of analcite positively depends on its concentration. In particular, at a minimum concentration of this silicon-containing mineral (100 mg/200 ml soil substrate), the average (hereinafter, averaged for different soil types and moisture contents) growth of phytomass of aboveground shoots of maize and wheat is 14 and 44%, respectively. At the same time, the root mass increases by 49 and 29% for maize and wheat, respectively. The relative turgidity of the leaves adds 26 and 30% on average, while the water deficit decreases by 33 and 23% for maize and wheat, respectively. At an analcite concentration of 200 mg per 200 ml soil substrate, the mass of the aboveground shoots of the test plants increases by 25 and 71%, for maize and wheat, respectively, while the roots add 55 and 29%, for maize and wheat, respectively. The relative turgidity of the leaves grows by 41 and 64% for maize and wheat, respectively. The water deficit decreases by 46 and 51% for maize and wheat, respectively. At a maximum concentration (300 mg per 200 ml soil substrate), analcite stimulates the accumulation of biomass by the aboveground shoots by an average of 31 and 84%, for maize and wheat, respectively. For the root systems, the stimulation makes up 59 and 82%, for maize and wheat, respectively. The relative turgidity of the leaves increases by 51 and 84%, for maize and wheat, respectively. The water deficit decreases by 62 and 66%, for maize and wheat, respectively.

The analysis of the interaction of two factors (analcite concentration and substrate moisture) has shown that the greatest protective effect is observed at a concentration of 200—300 mg/200 ml soil substrate per dish, at a substrate moisture content of 20%.

The soil type also significantly influences the stimulating effect of analcite. In particular, it has been found that in the sandy substrate (soil type No. 3) wheat and maize plants are more responsive to the application of analcite as compared with the plants cultivated in the soil mix (soil type No. 1) and the gray podzolic soil (soil type No. 2). In particular, this trend may be observed in the development of the root system of the test plants. Depending on the concentration of analcite and soil moisture, the mass of the roots of wheat plants in the sandy substrate increases 1.5—2.6 times, whereas that of maize plants grows 1.3—1.8 times as compared with the plants cultivated without analcite.

The ratio of the mass of aboveground parts (shoots: stems + leaves) to the mass of roots of wheat and maize plants cultivated in soil types No. 1 and No. 2 increases in the case of analcite application. The inverse correlation has been observed on the sandy substrate (soil type No. 3). Obviously, this is explained by the fact that these crops are demanding to soil fertility, so growing them on soil type No. 3 is a stress factor. Therefore, such stimulation of the development of the root system in wheat and maize in the sandy substrate (soil type No. 3) with the introduction of analcite at the studied concentrations also increases the adaptability of these crops to the deficit of organic nutrients.

In general, the highest ability to adapt to soil drought has been reported for the wheat and maize plants cultivated in soil type No. 1 with the application of analcite at a maximum concentration (300 mg/200 ml soil substrate).

The influence of analcite on the allelopathic and biochemical properties of the abovementioned types of soil substrates, at different moisture content, in the experiments with wheat and maize plants has been studied.

The results obtained by the direct biotesting method have shown that the use of analcite has a positive effect on the allelopathic activity of the soil.

In the experiment with wheat plants at a concentration of 100 mg analcite/200 ml soil substrate the allelopathic activity of soil type No. 1 and No. 3 has been recorded at the reference level (Fig. 5). The same trend is observed for soil type No.3 at a concentration 200 mg analcite/200 ml soil substrate at a moisture content of 20% and 40% of TSM. The stimulation of *L. sativum* root growth in soil type No.1 does not differ at a concentration of 200 mg and 300 mg analcite/200 ml soil substrate, at the same moisture content. This

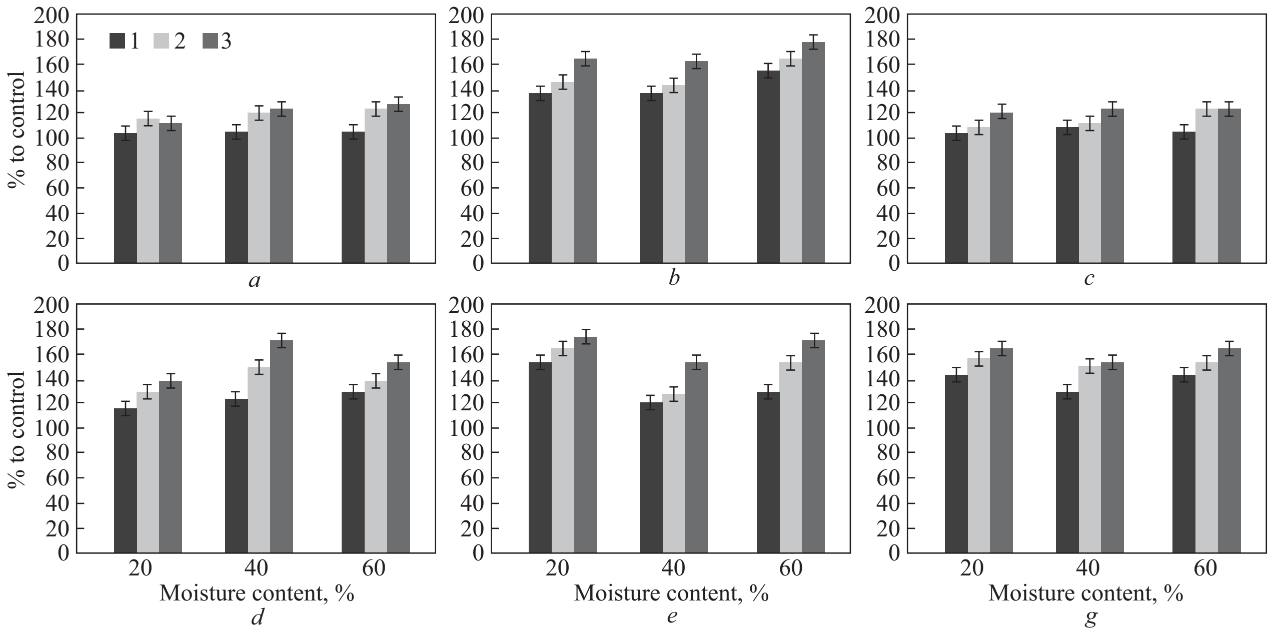


Fig. 5. Allelopathic activity of the soil under wheat and maize with the use of analcite, % to control: *a* (wheat), *g* (maize), greenhouse soil mix; *b* (wheat), *d* (maize), gray podzolic soil; *c* (wheat), *e* (maize), sand; *1* — 100 mg analcite/200 ml soil substrate, *2* — 200 mg analcite/200 ml soil substrate, *3* — 300 mg analcite/200 ml soil substrate

is also typical for variants with soil type No. 3 at a moisture content of 60% of TSM. The use of analcite at a concentration of 300 mg/200 ml soil substrate in soil type No. 2 has the most significant effect on the allelopathic activity. The best result in terms the stimulation of *L. sativum* root growth among all the analcite concentrations, 55—78% as compared with the reference, has been reported for a moisture content of 60% of TSM, which is the most optimal for plants. Also, there has been recorded a significant increase in the growth of biotest roots at a moisture content of 20 and 40% of TSM (by 37—65%, depending on the concentration of analcite).

It should be noted that the positive effect of analcite on the allelopathic activity of the studied soils is more evident in the experiments with maize plants (Fig. 5), where the stimulation of *L. sativum* root growth is higher as compared with most experiments with wheat. Even at an analcite concentration of 100 mg/200 ml soil substrate, there is an increase in the growth of biotest roots in all variants: 18—51%, at 20% of TSM and 21—30%, at 40% of TSM, depending on the type of soil.

In general, the highest growth-stimulating effect of analcite on bioassays (*L. sativum* root growth) has been reported at a concentration of 300 mg/200 ml soil substrate.

The biochemical state of the root environment has been assessed in more detail by the indicators of redox potential that is closely related to the conversion of organic matter and reflects the total effect of currently redox systems in soil [21].

The studies have shown that, in the case of analcite application, the redox potential of soil in the experiments with wheat (Fig. 6) exceeds the reference value 1.1—1.3 times. In this case, for soil type No. 2, at a moisture content of 40 and 60% of TSM, and for soil type No. 1, this effect becomes stronger as the concentration of analcite increases (up to 200 and 300 mg/200 ml soil substrate). At the same time, for soil type No. 3, the redox potential indicators at a moisture content of 40 and 60% of TSM remain at the same level regardless of analcite concentration, and for soil types No. 2 and No. 3, at a moisture content of

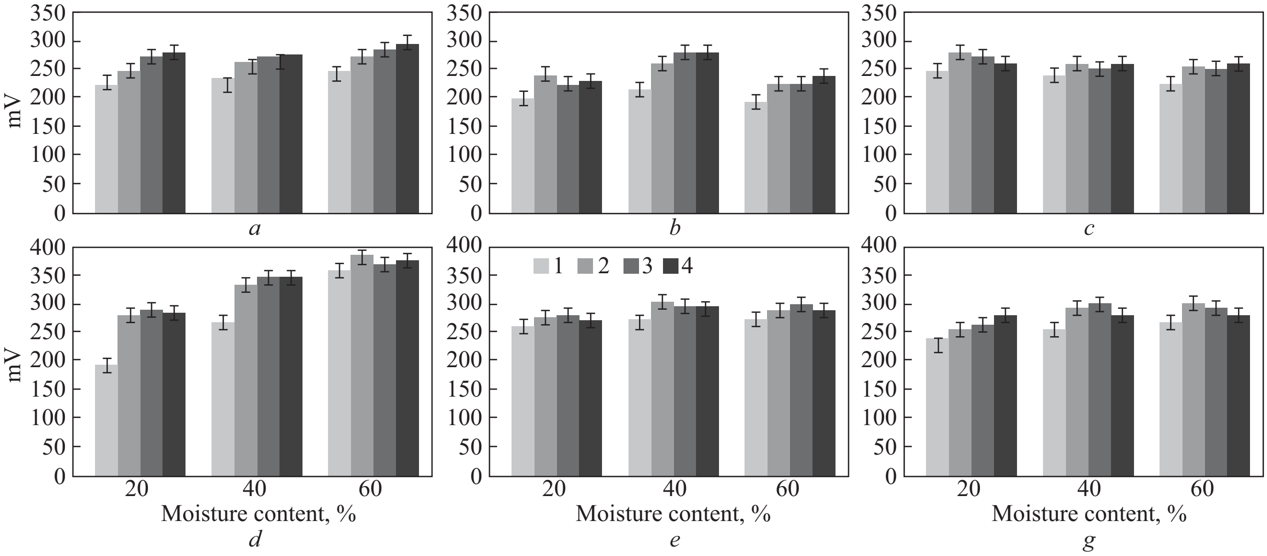
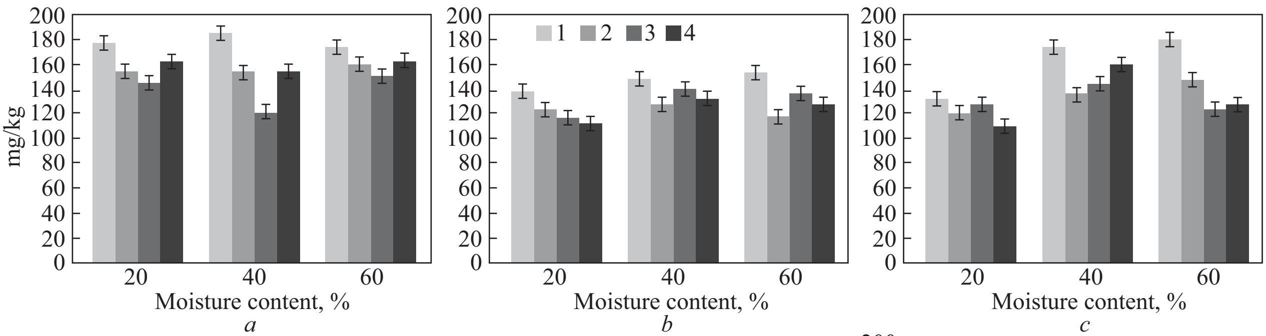


Fig. 6. Redox potential of the soil under wheat and maize in the case of the introduction of analcite, mV: *a* (wheat), *g* (maize), greenhouse soil mix; *b* (wheat), *d* (maize), gray podzolic soil; *c* (wheat), *e* (maize), sand; *1* — reference, *2* — 100 mg analcime/200 ml soil substrate, *3* — 200 mg analcime/200 ml soil substrate, *4* — 300 mg analcime/200 ml soil substrate



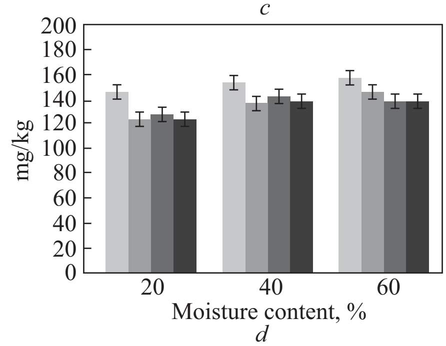


Fig. 7. The content of phenolic compounds in the soil under wheat and maize in the case of the introduction of analcite, mg/kg: *a* (wheat), *b* (maize), greenhouse soil mix, *c* (wheat), *d* (maize), gray podzolic soil; *1* — reference, *2* — 100 mg analcime/200 ml soil substrate, *3* — 200 mg analcite/200 ml soil substrate, *4* — 300 mg analcite/200 ml soil substrate

20% of TSM, they slightly decrease as the concentration of silicon-containing mineral increases to 200 and 300 mg/200 ml soil substrate.

A similar trend (increasing the redox potential in the case of the analcite application) has been observed for the maize plants (Fig. 6). It is especially evident of soil type No. 1, at a moisture content of 20 and 40% of TSM, for which the redox potential exceeds the reference value 1.4—1.5 and 1.2—1.3 times, respectively.

The accumulation rate, composition, and conversion of organic substances are determined by redox processes. Increasing redox potential in the case of analcite application indicates a low level of mobile and active organic compounds that may act as allelopathic agent and create phytotoxicity.

Since phenolic substances play an important role in the chemical interaction of plants because of resistance to microbiological action and the ability to accumulate in the root environment and to affect the growth and development of plants [2], their content in soil substrates with analcite has been studied.

In the model experiments with wheat and maize, in the case of analcite application, in all studied concentrations, the amount of free phenolic substances in the soil decreases 1.1—1.5 times as compared with the reference, which obviously indicates a greater intensity of moisturization processes under the influence of silicon-containing mineral (Fig. 7). At the same time, the accumulation of phenolic compounds in the reference sample indicates that humus-forming processes are disturbed, which can adversely affect the physiological condition of plants.

Thus, the use of analcite does not cause any phytotoxicity of the soil and helps to improve the allelopathic and biochemical characteristics of soil to stimulate the growth and development of plants, which is especially important at a low moisture content (20 and 40% of TSM).

Influence of analcite on the allelopathic and microbiological properties of the soil-plant system

The analcite effect on the allelopathic and microbiological properties of the soil under sugar beet when the mineral is introduced in the row spacing at a rate of 50 kg / ha has been analyzed. The field experiments have been conducted in the research fields of the Institute for Bioenergy Crops and Sugar Beets of the NAAS of Ukraine; the soil is low-humus chernozem (humus content 2.0—2.1%).

As a result of determining the allelopathic activity of the soil, it has been found that analcite stimulates the growth of bioassay (growth of *L. sativum* roots) by 29 and 26% after 3 and 6 months after application, respectively, which indicates the improvement of the growth and development conditions for plants (Table 1).

In the case of analcite appilication, the redox potential (at a rate of 50 kg/ha) exceeds the reference, which testifies to a low presence of labile organic compounds that may have allelopathic effects on plants, in the experiments (Table 2).

Phenolic compounds are precursors of humic substances, but in the mobile form they may be allelopathically active [2]. The content of free phenolic compounds in the soil with the application of analcite (50 kg/ha) decreases 1.6 and 1.4 times as compared with the reference, after 3 and 6 months after application, respectively (Table 3).

Hence, the introduction of analcite helps improve the humification process. In the reference sample, on the contrary, labile phenolic substances prevail, which may cause phytotoxicity of soil under certain conditions.

Table 1. **Allelopathic Activity of Soil after the Plantation of Sugar Beet with the Introduction of Analcite, a Growth in *Lepidium sativum* Roots (% reference)**

No.	Sampling time, months after the introduction of analcite (50 kg/ha)	Soil + analcite
1	3	129.4 ± 5.2
2	6	126.0 ± 5.0

Table 2. **Redox Potential in the Soil after the Plantation of Sugar Beet with the Introduction of Analcite, mV**

Sampling time, months after the introduction of analcite (50 kg/ha)	Reference	Soil + analcite
3	200.0 ± 5.1	245.0 ± 7.3
6	232.0 ± 6.9	279.0 ± 8.4

Table 3. **The Content of Phenolic Compounds in the Soil after the Plantation of Sugar Beet with the Introduction of Analcite, mg/kg**

Sampling time, months after the introduction of analcite (50 kg/ha)	Reference	Soil + analcite
3	110.1 ± 4.5	69.7 ± 3.5
6	105.2± 5.2	75.4 ± 3.8

The use of silicon-containing mineral analcite (50 kg/ha) improves the biochemical properties of the sugar beet root soil for 6 months, which has a positive effect on its allelopathic properties, as well as affects the microbiological activity of the soil. While studying the composition of the soil microbiocenosis, we have identified the groups of microorganisms that are most typical for allelopathic soil fatigue. They include microscopic fungi, spore-forming bacteria, actinomycetes, and nitrogen bacteria. This list may be extended, but contains the main indicator microorganisms that are sensitive to phytotoxins.

A microbiological analysis has been done by sowing soil suspensions in appropriate dilutions on agar nutrient media, in accordance with generally accepted methods [18]. The number of oligonitrophils (KAA), ammonifiers (MPA), micromycetes (Capek's medium), actinomycetes (KAA), spore-forming bacteria (Mishustin's medium), and cellulosolytic microorganisms (Hutchinson's medium) has been counted. The number of nitrogen-fixing microorganisms has been determined by application to the surface of Ashby's agar medium [22]. The total number of colonies, which is counted when sowing soil suspensions, is conditioned by the number of CFU (colony-forming units). The ratio of individual ecological and trophic groups of microorganisms (mineralization-immobilization coefficient) has been determined by K.I. Andreiuk and coauthors [23].

As a result of the research, it has been established that analcite (50 kg/ha) activates the accompanying microbial groups in the soil between the rows of sugar beet (Table 4).

Thus, the number of actinomycetes and micromycetes grows 5 times and almost 2 times, respectively. Consequently, the intensity of enzymes secreted by them increases, as a result of which the processes associated with the transformation of nitrogen and carbon compounds get intensified. The amount of spore-forming bacteria and cellulolytic microorganisms is not significantly affected by the application of analcite. A low cellulose activity of the latter is noted both in the reference and in the experimental soils (the decomposition of fiber is only 2.5—3.1%). However, bacteria dominate the reference sample, while fungi prevail in the experimental one.

Under the action of analcite (50 kg/ha), the pool of microorganisms that assimilate inorganic forms of nitrogen increases, with the growing index of mineralization-immobilization (by 0.7) indicating the intensification of the soil mobilization processes of the transformation of nitrogen compounds and related processes of mineralization of organic substances.

Overgrowth of soil lumps with nitrogen-fixing microorganisms is 100% in both cases, but in the experimental sample with analcite (50 kg/ha), their development is more intensive.

Hence, the application of silicon-containing mineral analcite (50 kg/ha) significantly improves the microbiological parameters of the soil. The results of research have allowed us to explain the ambiguity of the response of soil microorganisms to the introduction of silicon-containing minerals and, considering the microbiota an indicator of plant response to soil conditions, to predict their effect on the productivity of plant organisms. In

Table 4. **The Number of Microorganisms of the Main Taxonomic and Ecological Trophic Groups in the Soil after the Plantation of Sugar Beet with the Introduction of Analcite (50 kg / ha)**

No.	Ammonifiers, million	Oligonitrophils, million	Spore-forming bacteria, thousand	Micromycetes, thousand	Actinomycetes, million	Cellulosolytic m/o, thousand	% decomposition of cellulose	Nitrogen-fixing microorganisms, % overgrowth of soil lumps	Mineralization-immobilization coefficient
1	47.5±3.5	38.5±6.5	121.5±13.4	14.0±5.0	1.5±0.7	26.0±5.7	3.1	100	0.8
2	21.5±2.1	54.5±5.5	140.0±19.8	24.5±0.7	7.5±2.1	20.0±1.4	2.5	100	2.5

Note: 1 – reference, 2 – application of analcite (experiment).

addition, the analysis of the obtained data has shown the nature of the relationship between the microbiological and the enzymatic activity and may be used to improve the biological condition of the soil and to reduce soil fatigue after perennial plantation of crops.

In general, the studies have shown a positive effect of analcite at all concentrations on the physiological and biochemical properties of the plant-soil system under conditions of insufficient moisture, which contributes to optimizing the growth and moisture regime of winter wheat and maize. No phytotoxic manifestation of analcite has been reported. The allelopathic properties of the root environment of winter wheat, maize, and sugar beet improve as a result of decreasing content of free phenolic compounds and activating the redox and microbiological processes.

The introduction of effective and safe technology for the use of analcite is promising to raise the adaptability of plants to drought and to reduce the effects of soil fatigue.

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REFERENCES

1. Gomes, M. P., Garcia, Q. S., Barreto, L. C., Pimenta, L. P. S., Matheus, M. T., Figueredo, C. C. (2017). Allelopathy: an overview from micro- to macroscopic organisms, from cells to environments, and the perspectives in a climate-changing world. *Biologia*, 72(2), 113—129. https://doi.org/10.1515/biolog-2017-00019.
2. Li, Z.-H., Wang, Q., Ruan, X., Pan, C.-D., Jiang, D.-A. (2010). Phenolics and plant allelopathy. *Molecules*, 15(12), 8933—8952. https://doi.org/10.3390/molecules15128933.
3. Sherstoboeva, O. V., Demianiuk, O. S. (2003). Microbial biomass in soils of different ecosystems. *Collected works of Uman National University of Agriculture, Special Issue,* 306—310 [in Ukrainian].
4. Ellanska, N. E. (2008). Microbiological bases of soil monitoring. *Naukovy Visnyk Chernivetskoho Universitetu*, 416, 9—14 [in Ukrainian].
5. Kumar, S., Jakhar, S. R., Dahiya, S., Jangir, C. K., Meena, R. S. (2017). Soil sickness and productivity from ecological aspects. *J. Pharmacogn. Phytochem.*, 6(1), 827—831. URL: https://www.phytojournal.com/archives/?year=2017&vol=6&issue=6S&ArticleId=2912 (Last accessed: 06.04.2021).
6. Ma, B.-X., Cheng, D.-Y., Cui, J., Dai, C.-H. (2017). Effect of different allelochemicals on the growth and gene expression of beet seedlings. *International Conference on Energy, Environment and Sustainable Development (EESD, 21-22 Apr 2017, Phuket)*. Phuket, 77—81. https://doi.org/10.12783/dteees/eesd2017/11980.
7. Zaimenko, N. V., Pavliuchenko, N. A., Ellanska, N. E., Kharytonova, I. P. (2014). Influence of drought on allelopathic, biochemical and microbiological properties of plants-soil-microorganisms system. *The Journal of V.N. Karazin Kharkiv National University. Series: biology*, 20(1100), 286—294 [in Russian].
8. Moshoeshoe, M., Nadiye-Tabbiruca, M. S., Obuseng, V. (2017). Are view of the chemistry, structure, properties and applications of zeolites. *American Journal of Materials Science*, 7(5), 196—221. https://doi.org/10.5923/j.materials.20170705.12.
9. Zaimenko, N. V., Slyusarenko, O. M., Yunosheva, O. P. (2017). Application of silicon-containing mixtures slows down the migration rates of radionuclides in soil-plant system. *Scientific Bulletin of UNFU*, 27(1), 106—108. https://doi.org/10.15421/40270123 [in Ukrainian].
10. Zaimenko, N. V., Didyk, N. P., Pavliuchenko, N. A., Ivanytska, B. O., Kharytonova, I. P., Rositska, N. V. (2018). Natural silicates mixed with organic fertilizers enhance corn adaptation to salt stress and improve physical characteristics of sandy soil. *Journal of Crop Improvement,* 32(2), 188—207. https://doi.org/10.1080/15427528.2017.1405856.
11. Nakhli, S. A. A., Delkash, M., Bakhshayesh, B. E., Kazemian, H. (2017). Application of zeolites for sustainable agriculture: a review on water and nutrient retention. *Water, Air, & Soil Pollution*, 228(12), id. 464. https://doi.org/10.1007/s11270-017-3649-1.
12. Zaimenko, N. V. (2008). *Scientific principles of structural and functional design of artificial biogeocenoses in the soil-plant-soil system*. Kyiv: Naukova Dumka [in Ukrainian].
13. Artyszak, A. (2018). Effect of silicon fertilization on crop yield quantity and quality — a literature review in Europe. *Plants*, 7(3), 54. https://doi.org/10.3390/plants7030054.
14. Ellanska, N. E., Zaimenko, N. V., Yunosheva, O. P. (2015). The soil microbial coenosis state under various crops in case of introducing the mixture of silicon-containing minerals. *Agricultural Microbiology,* 22, 30—37 [in Ukrainian].

15. Ellanska, N., Yunosheva, O. (2016). The siliceous mixtures influence on microbiological transformation processes of nitrogen in soil under wheat. In *Agrobiodiversity for Improving Nutrition, Health and Life Quality 2016,* Nitra: Slovak University of Agriculture. P. 83—86. https://doi.org/10.15414/abd2016.9788055215860 [in Russian].
16. Voytsehivska, O. V., Kapustyan, A. V., Kosyk, O. I. (2010). *Plant physiology*: *practicum*.-Lutsk: Teren [in Ukrainian].
17. Kozhushko, N. N. (1988). Assessment of drought resistance of field crops. In *Diagnostics of plant resistance to stress effects. Methodical guidance*. Leningrad: VIR Publishing House. 10—25 [in Russian].
18. Modern methods in allelopathic research. Methodical manual. (2021). Kyiv: Lira-K Publishing House [in Ukrainian].
19. Labuda, S. Z., Vetchinnikov, A. A. (2011). Soil susceptibility on reduction as an index of soil properties applied in the investigation upon soil devastation. *Ecological Chemistry and Engineering S*, 18(3), 333—344.
20. Fiedler, S., Vepraskas, M. J., Richardson, J. L. (2007). Soil redox potential: importance, field measurements and observations. *Advanced in Agronomy*, 94, 1—54. https://doi.org/10.1016/S0065-2113(06)94001-2.
21. Husson, O. (2013). Redox potential (Eh) and pH as drivers of soil/plant/microorganisms systems: a transdisciplinary overview pointing to integrative opportunities for agronomy. *Plant Soil*, 362(1—2), 389—417. https://doi.org/10.1007/s11104-012-1429-7.
22. *Methods of Soil Microbiology and Biochemistry.* (1991). (Ed. D. G. Zvyagintsev). Moscow: MSU Publishing House [in Russian].
23. Andreyuk, K. I., Iutynska, G .O., Antipchuk, A. F., Valagurova, O. V., Kozyrytska, V. E., Ponomarenko, S. P. (2001). *Functioning of microbial coenoses of soil in the conditions of anthropogenic loading*. Kyiv: Oberegy [in Ukrainian].

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ЗАСТОСУВАННЯ КРЕМНІЙВМІСНОГО МІНЕРАЛУ АНАЛЬЦИМУ ДЛЯ ОПТИМІЗАЦІЇ ФІЗІОЛОГО-БІОХІМІЧНИХ, АЛЕЛОПАТИЧНИХ ТА МІКРОБІОЛОГІЧНИХ ВЛАСТИВОСТЕЙ СИСТЕМИ РОСЛИНА–ҐРУНТ

Вступ. Глобальні кліматичні зміни спричинюють нерівномірність опадів, що погіршує водно-фізичні властивості ґрунту та порушує мікробіологічні процеси. Як наслідок може виникати алелопатична ґрунтовтома.

Проблематика. Пошук й розроблення нових ефективних та безпечних заходів регулювання фізіолого-біохімічного, алелопатичного й мікробіологічного стану системи рослина–ґрунт є нагальною необхідністю за умов нестабільної екологічної ситуації.

Мета. Оптимізувати фізіолого-біохімічні, алелопатичні й мікробіологічні характеристики системи рослина–ґрунт за умов недостатнього вологозабезпечення та ґрунтовтоми шляхом застосування кремнійвмісного мінералу анальциму.

Матеріали й методи. У модельних вегетаційних дослідах вивчали вплив кремнійвмісного мінералу анальциму у концентрації 0, 100, 200 та 300 мг на 200 мл ґрунтового субстрату на показники росту, водного режиму рослин пшениці та кукурудзи за різних умов зволоження (20, 40 та 60% повної вологоємкості) та типу ґрунтового субстрату. У польовому експерименті анальцим вносили в ґрунтовий субстрат перед посадкою насіння під рослини цукрового буряку у нормі 50 кг/га. У модельних та польових дослідах аналізували перебіг редокс-процесів, вміст фенолів та мікробіологічні показники ґрунту.

Результати. Використання анальциму оптимізувало показники росту, водного режиму рослин, а також алелопатичні характеристики системи рослина–ґрунт шляхом зниження вмісту вільних фенолів, активізації розвитку мікробних ценозів й редокс-процесів. При цьому відмічено відсутність фітотоксичного прояву анальциму,

Висновки. Запропоновано застосування анальциму для покращення фізіолого-біохімічних, алелопатичних й мікробіологічних властивостей системи рослина–ґрунт. Окреслено перспективи використання мінералу для підвищення адаптаційної здатності рослин за умов посухи та для подолання наслідків ґрунтовтоми.

Ключові слова: озима пшениця, кукурудза, цукровий буряк, анальцим, мікробіоценоз, алелопатично активні сполуки, вологозабезпечення, ґрунтовтома.