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THE INFLUENCE OF PHOSPHOGYPSUM ON THE SALT COMPOSITION OF SALINATED SOIL

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Abstract. *Global climate changes in many countries of the world lead to the need to use irrigation as a driving factor for obtaining guaranteed and stable harvests of agricultural crops. Irrigation with water of different quality leads not only to an increase in the yield, but also to a change in the salt composition of the soil. The change in the salt composition of soils occurs much faster during irrigation with mineralized water, which leads to the accumulation of soluble salts in the arable layer of the soil and the deterioration of the composition of the soil absorption complex. Accumulation of sodium ions leads to salinization of irrigated soils. It is possible to stop or suspend the salinization processes by introducing chemical melioration with calcium-containing meliorants. As an ameliorant in this work, the use of a by-product of the mineral fertilizers production – phosphogypsum, which contains a significant amount of calcium (up to 95%), replacing exchangeable sodium in the soil absorption complex is proposed. Our researches are related to the establishment of optimal calculation norms and terms of phosphogypsum application, their influence on the change in the components of the soil's saline extract. The research was conducted on soils that had been irrigated with mineralized water from the Samara River (Ukraine) for a long time (over 50 years). According to the amount of exchangeable sodium, the soils of the experimental sites belonged to low-sodium soils with physical signs of salinization processes, and according to the content of toxic salts-moderately saline. For phosphogypsum in the soil-ameliorative conditions of the Northern Steppe of Ukraine, the ameliorative, agronomic, and ecologically safe rates of introduction in spring and autumn were calculated. The scheme of experiments provided options with sprinkler irrigation and without irrigation. The composition of the aqueous extract was determined by indicators of anion-cation content. During the research, a gradual decrease in the number of sulfates was observed: by 1.5% in the second year after exposure, and by 7.5% in the third year after exposure to phosphogypsum. The number of hydrocarbons decreased in irrigated areas where phosphogypsum was applied, and an increase in their content was observed in areas where irrigation was not carried out. Irrigation options were characterized by a significant increase in the content of chlorine ions, which is explained by the arrival of these ions exclusively with irrigation water. The degree of salinity was determined by pH and sodium adsorption ratio (SAR). Based on these indicators, it was established that the soils are slightly saline in all variants of the experiments. As a result of multi-year research, a positive effect of phosphogypsum melioration on the anion-cation composition of water extract and the degree of soils salinity irrigated with mineralized water for a long time was noted. According to the anionic composition, the chemistry of the soils in the experimental plots was sulfate in the variants where phosphogypsum was applied and vegetation irrigation was carried out and without irrigation, while in the control plots (without phosphogypsum and without irrigation) soda-sulfate chemistry was characterized.*

The chemistry of the soils in the experimental areas according to the cationic composition was sodium in all versions of the experiments. According to the sodium-adsorption ratio (SAR), the degree of soil salinization belonged to the slightly saline type, while the average type of salinity remained in the control plots without phosphogypsum.
Keywords: *anionic-cationic composition, soil water extraction, phosphogypsum, sodium adsorption ratio*

Introduction. The global food crisis is growing every year due to global climate change. The year 2022 showed that the lives of almost 120 million people depend on agricultural products produced on the territory of Ukraine. Therefore, more and more agricultural producers in the Steppe and Forest-Steppe zones of Ukraine are switching to irrigated agriculture to obtain guaranteed stable and high yields of agricultural crops. The role of irrigation reclamations and their impact on the environment will increase every year [1].

According to the strategic ecological assessment of irrigation and drainage in Ukraine by 2030, in order to overcome the deficit of water supply, it is necessary to carry out permanent irrigation on the area of 18.7 million hectares (60 %) of arable land and periodic irrigation on the territory of 4.8 million hectares (15 %). The area of insufficiently humid, arid, dry, and very dry wetlands has increased by 10 % over the past 25 years. The change in climatic conditions led to the expansion of the natural and climatic zones boundaries of Ukraine in the northern direction by 100–1 50 km [2].

The quality of irrigation water in Ukraine changes significantly every year (Rudakov et al., 2020; Andrieiev et al., 2022) [3–5]. The area with irrigation water of the II quality class “limitedly suitable” according to agronomic criteria increased by 14 % (compared to 2014), which in 2018 amounted to 388,739 thousand ha (84.2 %) [2].

The practice of irrigating mineralized surface soils in the world is quite accepted [6, 7] and groundwater [8]. Such irrigation is always accompanied by certain processes of soil degradation [9]. Saltation occurs [10], physical properties deteriorate, and soil fertility significantly decreases.

One of the well-known methods of chemical soil reclamation to combat negative processes during irrigation is the use of gypsum [11, 12]. Many scientific works in the world and domestic practice of irrigated agriculture devoted to this issue are highlighted [13–16].

Experiments on plastering of soils irrigated with mineralized waters were conducted by many domestic scientists [17–19]. As a result of the conducted research, it was established that plastering increases the content of metabolizable and absorbed calcium and significantly reduces the amount of absorbed sodium. When applying even high doses of gypsum, it is not possible to bring the degree of saturation of the soil solution with calcium to the required level in the absence of watering. In the scientific works by the authors from Europe and Asia, patterns of changes in soil properties under the influence of irrigation were established and methods were developed to reduce the adverse effect of low-quality irrigation water on soils [9, 15, 20–23]. Among them, plastering and deep plantation plowing remain the most studied. Scientists emphasize that plastering is a method that limits or weakens the process of salting, but does not eliminate it completely [24, 25].

The effect of chemical meliorants consists in squeezing out or creating an obstacle for the entry of sodium into the soil absorption complex. Due to that, the physical properties of the soil change, and the productivity of agricultural crops increases. Due to the displacement of sodium from the soil absorption complex by calcium or other di- or three-charged cations, the mobility of soil colloids decreases, alkalinity decreases, the availability of nitrogen, phosphorus, potassium, and calcium for plants increases, and microbiological processes are activated [14, 26–29].

Taking into account the accumulated scientific and practical experience, the problem of chemical reclamation of irrigated soils and irrigation water remains insufficiently studied and relevant today. The questions about the expediency and effectiveness of plastering chernozems with a weak degree of salinization are not resolved. There are objections to approaches to the calculation of meliorant doses. The quantitative component of the gypsum interaction with soil and water, depending on variable natural and climatic conditions, is insufficiently covered. Environmental aspects of the meliorants usage are problematic, which necessitates the search for new, more effective measures from the point of view of resource and energy conservation and environmental safety [24, 30].

The need for chemical reclamation of irrigated lands is due to salinization of soils and their degradation: compaction, destructuring, crust formation, etc. [27, 31, 32]. Uncontrolled irrigation in the 1960s and 1980s with high rates of low-quality water and non-compliance with irrigation technology caused a decrease in soil fertility and deterioration of the ecological and reclamation status of irrigated areas. Unfounded irrigation regimes on chernozems are often accompanied by such degradation processes as flooding, secondary salinization, salinization, violation of the gas regime, dehumification, etc. [33]. Thus, there is a need for a comprehensive study of changes in the agroecological state of soils that have been under the influence of mineralized water irrigation for a long time. As a result of long-term irrigation with water of different quality in the territory of the Northern Steppe of Ukraine, an acute problem of secondary salinization and salinization of lands arose [34].

Material and methods. Degradation processes of irrigated soils were studied thanks to the systematic analysis of the results by domestic and foreign scientists. Methods of analysis and synthesis were used to solve the set goal. To establish the optimal rate and method of applying phosphogypsum, experimental studies were conducted in field and laboratory conditions. The influence of calcium-containing ameliorants on the physical properties of the soil was determined in the field, and the chemical composition of the soil was determined in the laboratory. The reliability of the obtained results was checked by statistical evaluation methods.

The experimental researches covered plots with a total area of 60 hectares in the state enterprise “the Dnipro research station’s experimental farm of the institute of vegetable and melon growing of the Ukrainian national academy of sciences” in the village of Oleksandrivka, Dnipro district, Dnipropetrovsk region (2010–2021) near the lake on the samara river. (Fig. 1).

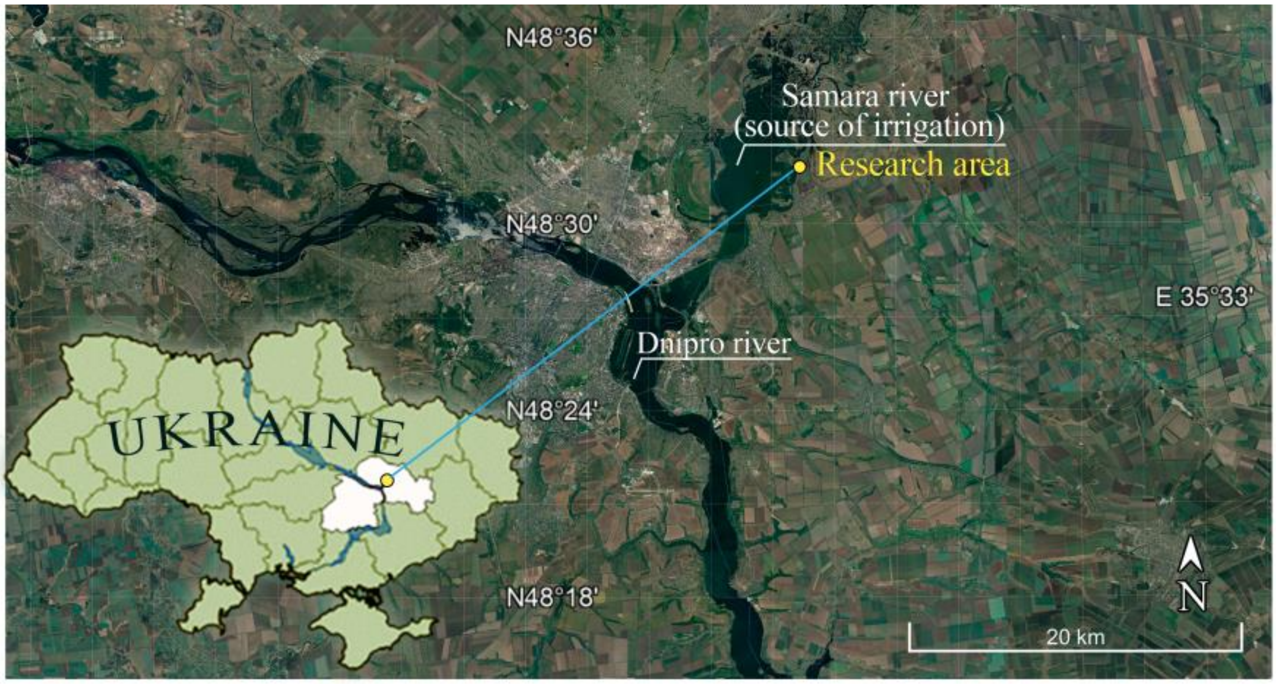

Fig. 1. The place of research

The anion-cation composition of the water extract of the arable soil layer (30 cm) indicates the type or chemistry of salinization [35]. Laboratory studies were carried out in certified laboratories in Dnipro according to the regulatory and methodological bases in Ukraine.

The farm has been irrigated with Irtec hose-drum sprinklers with mineralized water (more than 2 g/l) from the Samara River for 50 years [36]. During the three years of research, the irrigation rate during the growing season was 1150 m^3/ha, 1300 m^3/ha and 1700 m^3/ha, respectively. Irrigation water belongs to the II quality class in terms of toxic effects on plants and the danger of salinization and salinization. In accordance with agronomic criteria, the chemical type of water was established as chloride-sulfate sodium-magnesium for almost the entire period, and chloride-sulfate magnesium-sodium (table 1).

1. Chemical composition of irrigation water by years of research

№	Main indicators (irrigation source – reservoir on the Samara River)	Unit of measurement	Results of water analysis by year		
			First year	Second year	Third year
1	pH	-	8.10	8.01	8.33
2	Rigidity	meq/dm^3	23.9	24.7	25.2
3	Alkalinity	meq/dm^3	5.50	5.53	6.25
4	Dry residue	mg/dm^3	2290.0	2670.0	3090.0
5	Sulfates	mg/dm^3	889.4	920.2	1154.0
6	Chlorides	mg/dm^3	493.8	490.2	520.0
7	Hydrocarbons	mg/dm^3	336.5	380.6	551.0
8	Calcium	mg/dm^3	176.1	220.9	203.0
9	Magnesium	mg/dm^3	182.1	200.7	201.4
10	Potassium + sodium	mg/dm^3	322.7	460.5	470.3
11	Sum of ions	mg/dm^3	2229.8	2670.0	3089.0

During the research, agricultural crops were alternated in the following crop rotation: spring barley, winter wheat, winter wheat, corn for grain, winter wheat.

The soil cover is represented by ordinary low-humus chernozems leached from the loam forest. This is confirmed by the morphological and physico-mechanical indicators of the soil: the 0−45 cm soil layer contains 71.02−74.0 % of physical sand and 28.98−26.0 % of physical clay, which, according to N.A. Kachinsky, corresponds to light loamy soil; the content of humus in the arable layer (0–30 cm) is 2.01–2.50 %, with depth the content of humus gradually decreases (at a depth of 90–105 cm – 0.3 %). Salinity processes are observed: pH=7.5, the content of toxic salts changes to 0.48 % (medium salinity).

The soils of the experimental areas have signs of salinity: in a wet state, the soil is highly plastic, viscous, sticky, swells strongly, and easily peptizes; when drying, the soil mass is compressed, which gives low water permeability. At the same time, the amount of exchangeable sodium is 3.64 %; the absorption capacity of the soil absorption complex is 20.1–26.47 meq per 100 g of soil, which are not characteristic indicators of saline soils. In order to determine the reasons for such an unsatisfactory physical condition of the experimental soils and establish measures to stop the degradation processes, many years of field research were laid. The searches are related to the analysis of the physical and chemical parameters of the soil through the control of the values of the soil's water extract characteristics during the years of research.

During the research, large amplitudes of fluctuations in daily and annual air temperatures were observed. Over the years of observation, a greater amount of atmospheric precipitation fell in the warm period of the year, but it was characterized by high intensity, which is ineffective for growing agricultural crops. The hydrothermal coefficient varied from 0.95 (2012) to 3.52 (2014).

As a calcium-containing meliorant, phosphogypsum was chosen like a by-product of the mineral fertilizers production. To prevent irrigation salinization of the soil, phosphogypsum from the Dnipro Mineral Fertilizer Plant (Kamyanske), Ukraine was used.

Norms of phosphogypsum application were calculated according to the Pfeffer method in the modification of Molodtsov and Ignatova, 1990 for the displacement of exchangeable sodium for low-sodium brines; according to O.M. Grinchenko, 1980, determined by the method of additional absorption of calcium by the soil; the norm was calculated by the coagulation-peptization method according to B.I. Laktionov, 1963. The reclamation norms are 1.4 t/ha, 3 t/ha, 6 t/ha, respectively, according to the methods proposed above. For the climatic zone of the Northern Steppe of Ukraine, the recommended agronomic norm is 6 t/ha. Since a by-product of the mineral fertilizers production containing specific impurities was chosen as a chemical ameliorant, an environmentally safe application rate of 10.3 t/ha was calculated. The calculated norms should not exceed the ecologically safe ones.

Phosphogypsum was applied to the soil with a reserve for three years with and without irrigation (table 2). Ameliorant was applied in 2010, 2014, and 2018 under spring barley, grain corn, and winter wheat, respectively. Phosphogypsum was applied for cultivation in the spring (at the rate of 1.4 and 3 t/ha) and in the fall for the main tillage (at the rate of 6 t/ha).

2. Scheme of the field experiment

Providing moisture	Variant	The rate of phosphogypsum application
Without irrigation	V1	Control without phosphogypsum
With irrigation	V2	Control without phosphogypsum
Without irrigation	V3	With the introduction of phosphogypsum under cultivation in the spring at the rate of 1.4 t/ha
	V4	With the introduction of phosphogypsum under cultivation in the spring at the rate of 3 t/ha
	V5	With the introduction of phosphogypsum in the fall under the main tillage at the rate of 6 t/ha
With irrigation	V6	With the introduction of phosphogypsum under cultivation in the spring at the rate of 1.4 t/ha
	V7	With the introduction of phosphogypsum under cultivation in the spring at the rate of 3 t/ha
	V8	With the introduction of phosphogypsum in the fall under the main tillage at the rate of 6 t/ha

Results and discussion. Irrigationally saline soils (irrigated with water of the II quality class for 50 years) and the change in their chemical composition when phosphogypsum was applied were chosen as the object of research.

The subject of research is the salt regime of the soil, the change of chemical and physical properties of irrigated soils under the influence of chemical melioration with phosphogypsum.

The main goal of the research is to evaluate the effect of phosphogypsum as a chemical ameliorant on the chemical composition of soils with signs of salinity during long-term irrigation with water of the II quality class.

The chemical composition of the aqueous extract of the soil during the years of research was controlled by indicators of anion-cation composition. In fig. 2 shows the average values of the analyzes of the aqueous extract by anions, and Fig. 3 – cation composition of the soil in meq/100 g of soil.

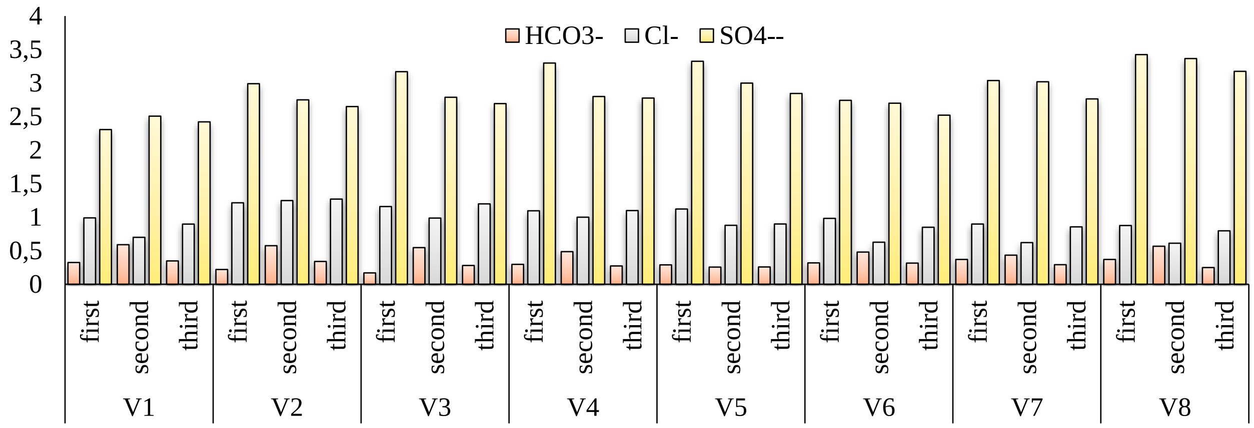

Fig. 2. Anionic composition of aqueous soil extract in the first three years of research, meq/100 g of soil

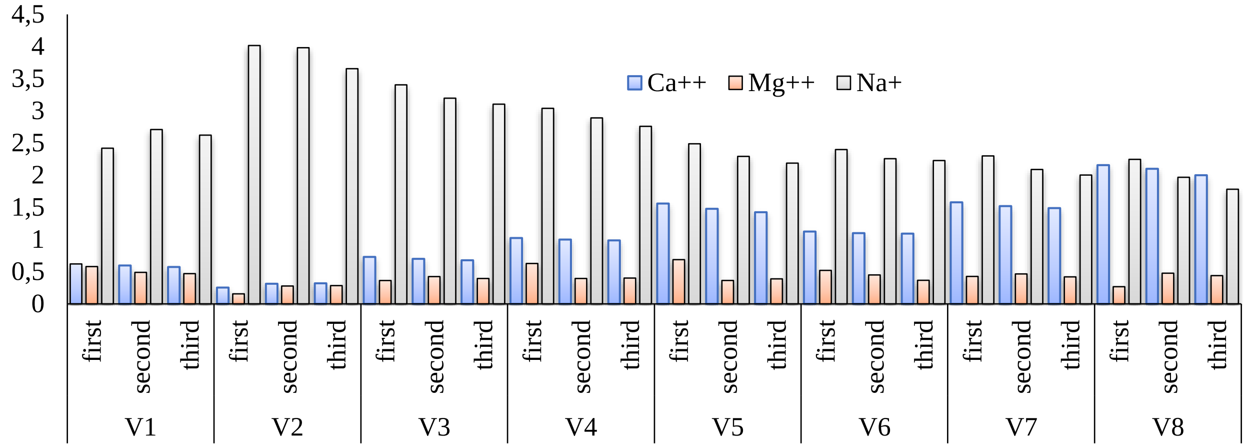

Fig. 3. Cationic composition of the soil's aqueous extract in the first three years of research, meq/100 g of soil

Over the years of observation, there was a decrease in sulfate ions in the control variant during irrigation (Table 1, variant V2). This can be explained by the process of washing out sulfates with irrigation water. The absence of irrigation on the control option led to an increase in SO_4^{-2} ions in the second year by 0.20 meq/100 g of soil, compared to the first, and a further decrease in the third year. The trend of increasing sulfates for the second year can be explained by the increase in the average annual air temperature compared to multi-year values. This made it possible to draw up sulfates from the lower layers of the soil profile during this period.

It can be seen from the graphs (Fig. 1) of the anionic composition that there is an increase in sulfate ions in relation to the control without irrigation and without the addition of phosphogypsum for all years of observation. The average indicators of the number of SO_4^{-2} ions compared to the control in the absence of watering increased by 18 %. This trend proves the theory of sulfates entering the soil during irrigation together with irrigation water. On the control options without irrigation, the amount of sulfates in the arable layer of the soil gradually decreased, with their highest value in the second year of observations (2.51 meq/100 g of soil).

The addition of phosphogypsum in areas without irrigation (Table 1, option V8) led to an increase in the concentration of SO_4^{-2} at all application rates, compared to the control option. In numerical form, the average values are 2.67–3.43 meq/100 g of soil, which is 0.31-1.07 meq/100 g of soil more compared to the option without irrigation. Options 6, 7 and 8 tend to increase the sulfate ion in proportion to the increase in the rate of phosphogypsum application. A decrease in concentration was observed in the long-term effect: a decrease of up to 1.5 % in the second year after exposure, and by 7.5 % in the third year after exposure.

During irrigation with the addition of phosphogypsum, the average values of SO_4^{-2} ions increased by 0.11–0.35 meq/100 g of soil over the entire observation period, compared to the irrigated control, and by 0.53–0.77 meq/100 g of soil in the control without irrigation. The content of SO_4^{-2} in the absence of irrigation is proportional to the rate of the phosphogypsum addition and decreased over the years of research. The content of sulfates decreased by 17.8% compared to the first year in the 3rd option in the third year of the post-action, and by 18 and 16.9 % in the options 4 and 5, respectively, which is 4.5–27 % more compared to options without irrigation. This is explained by the process of leaching SO_4^{-2} ions with irrigation water [33].

During the observation period, the number of hydrocarbons changed chaotically without a clear pattern. A certain regularity of the decrease in the amount of HCO_3^{-1} during irrigation with the addition of phosphogypsum, and the increase of indicators in the absence of irrigation with the addition of phosphogypsum, was established. Thus, the amount of HCO_3^{-1} decreased by 0.04–0.06 meq/100 g of soil in the areas where irrigation was carried out and phosphogypsum was applied in relation to the control areas where only irrigation was carried out without ameliorants. Compared to non-irrigated control options, the absence of irrigation with the addition of phosphogypsum led to a decrease in HCO_3^{-1}indicators by 0.03–0.07 meq/100 g of soil.

The concentration of hydrocarbons did not change significantly when the rate of phosphogypsum application was changed. In the irrigated variants, there was an increase in HCO_3^{-1} at the rate of application of 3 t/ha to 3 % compared to the rate of 1.4 t/ha, and a decrease of 10.7 % at the rate of 6 t/ha, while in the absence of irrigation this difference increased gradually by 8 % and then by 4 %.

It is known that chlorine ions are the most toxic for plants. Hypothetical toxic compounds formed with chlorine slow down the growth and development of plants. All chlorine salts are toxic to crops [27], but Na_2SO_4 is more toxic to some crops than NaCl, and vice versa to corn [14]. Whereas sulfur, which is part of the SO_4 ion, is more important in the development of plants and is a component of many cell components. Sulfur takes part in redox processes and energy exchange, plays a major role in the formation of properties and structural transformations of protein molecules [37].

Chlorine ions increased their concentration in irrigated areas during the entire period of observation, which is explained by the arrival of ions exclusively with irrigation water. There was a 1.5-fold increase in chlorine when irrigated in control plots compared to plots where irrigation was not carried out. Chemical amelioration with phosphogypsum on irrigated areas showed a positive tendency to decrease chlorine concentration by 13–34%, compared to the irrigated control option (V2). While the introduction of phosphogypsum in the absence of irrigation did not significantly affect the concentration of chlorine in the soil, namely: at the norm of 1.4 t/ha, the average indicators in the years of research compared to the non-irrigated option remained at the level of 0.85 meq/100 g of soil, and at rates of 3 and 6 t/ha decreased by 8.5 and 14.7 %, respectively. Also, different rates of phosphogypsum application did not affect the change in chlorine concentration, although without irrigation a slight decrease in Cl was observed when the rate was increased by 0.085 and 0.022 meq/100 g of soil. The absence of irrigation in the control areas did not show a significant pattern of changes in chlorine concentration, while in the reclamation area, a decrease of the ion was observed in the second year after the action by 32–15 % due to the redistribution of salts with an increase in SO_4 ions.

The type or cheminism of salinization was determined by the ratios of the largest anions-cations given in the table. 2. Application of phosphogypsum with and without irrigation, according to the anionic composition of the aqueous extract of the soil, has a sulfate type of salinization. The soda-sulfate type (SST) of salinization was observed in the control plots without the phosphogypsum addition and without irrigation in the first year, and in the other years of observation, only the sulfate type (ST) of salinization was noted.

The degree of salinity equivalent to chlorine and the amount of toxic salts in percentages in all variants of experiments were determined by combining anions and cations into hypothetical molecules of the appropriate amount (meq/100 g of soil), the results of which are shown in Table 3.

The SAR indicator for the set data range of all options except the first defines the degree of soil salinity as slightly saline. For the first option, according to the range of SAR ratios, salinity is characterized by an average degree. Control plots without irrigation were characterized by increased SAR values of 0.56 units in the second year. There was a similar trend with sulfates. The explanation of this phenomenon is due to the influx of sodium sulfate from the lower layers of the soil profile into the arable layer during this period.

3. Cheminism and the soils salinity degree of the experimental site

Research variant		V1			V2			V3			V4		
Degree of salinity / chemistry (type) of salinity		eCl, meq	Stox.salts, %	cheminsim (type)	eCl, meq	Stox.salts, %	cheminsim (type)	eCl, meq	Stox.salts, %	cheminsim (type)	eCl, meq	Stox.salts, %	cheminsim (type)
A year of research	1st	0.61	0.21	SST	1.39	0.3	ST	1.39	0.37	ST	1.39	0.39	ST
	2nd	1.39	0.32	ST	1.69	0.35	ST	1.49	0.38	ST	1.52	0.39	ST
	3rd	0.76	0.29	ST	1.99	0.36	ST	1.63	0.35	ST	1.96	0.37	ST

Research variant		V5			V6			V7			V8		
Degree of salinity / chemistry (type) of salinity		eCl, meq	Stox.salts, %	cheminsim (type)	eCl, meq	Stox.salts, %	cheminsim (type)	eCl, meq	Stox.salts, %	cheminsim (type)	eCl, meq	Stox.salts, %	cheminsim (type)
A year of research	1st	1.7	0.4	ST	1.6	0.58	ST	1.5	0.42	ST	1.5	0.41	ST
	2nd	1.62	0.38	ST	1.51	0.41	ST	1.41	0.41	ST	1.48	0.41	ST
	3rd	1.88	0.38	ST	1.75	0.4	ST	1.56	0.4	ST	1.48	0.41	ST

The degree of soil salinization can also be determined according to FAO standards by the sodium-adsorption ratio (SAR) [38]:

$$SAR = \frac{Na^{+}}{\sqrt{0.5(Ca^{2+}+Mg^{2+})}},$$

where Na^{+}, Ca^{2+} and Mg^{2+} – the content of the corresponding ions in the water extract of the soil, meq/100 g of soil

For the first three years of research, the SAR values of the correspondingly obtained cation indicators are shown in Table 4.

The lowest SAR indicators were observed in the third year after the application of phosphogypsum as a chemical meliorant at a depth of 0–105 cm. The most significant decrease in SAR occurred with the application of phosphogypsum at rates of 3 and 6 t/ha with irrigation and without it at all rates (recommended rate of 6 t/ha).

4. Indicators of the sodium-adsorption ratio by research options in the years of observation

Research variant	Retrospective year	pH	SAR
V1	first	7.5	3.12
	second	7.4	3.68
	third	7.5	3.63
V2	first	7.4	8.87
	second	7.2	7.33
	third	7.4	6.65
V3	first	7.17	4.61
	second	6.7	4.26
	third	7.2	4.24
V4	first	7.29	3.34
	second	6.89	3.46
	third	7.26	3.31
V5	first	7.37	2.35
	second	6.97	2.39
	third	7.34	2.30
V6	first	7.22	2.64
	second	6.75	2.56
	third	7.21	2.61
V7	first	7.36	2.30
	second	6.91	2.10
	third	7.3	2.05
V8	first	7.43	2.04
	second	7	1.73
	third	7.38	1.61

The phosphogypsum addition had a positive effect on the physical properties of the arable layer of the soil (Table 5).

5. Change of physical indicators of soil according to research options (soil layer 0-30 cm)

Research variant	Density of soil structures, g/cm^3			Soil porosity, %			Soil permeability, mm/min		
	1styear	2rdyear	3thyear	1styear	2rdyear	3thyear	1styear	2rdyear	3thyear
V1	1.37	1.35	1.35	50.20	50.40	50.50	2.14	2.07	2.00
V2	1.36	1.40	1.39	47.28	47.20	47.10	1.10	1.14	1.10
V3	1.24	1.25	1.20	52.00	52.00	52.35	2.48	2.45	2.50
V4	1.22	1.23	1.19	52.41	52.14	52.76	2.50	2.50	2.58
V5	1.21	1.21	1.17	52.83	52.02	53.00	2.51	2.52	2.60
V6	1.27	1.28	1.23	49.45	49.40	49.51	1.70	1.60	1.81
V7	1.25	1.24	1.20	49.98	50.00	49.91	1.73	1.71	1.89
V8	1.22	1.26	1.18	50.00	50.10	50.20	1.79	1.77	1.90

The phosphogypsum addition significantly affected the density indicators in the direction of improvement (Table 4). Even with the phosphogypsum addition, there was a tendency to increase the density in the irrigated options, compared to the non-irrigated areas. A tendency to increase soil density in dry years was also observed. The lowest density indicators in the variants without irrigation were noted in the first year after the effect when phosphogypsum was re-applied. The value of the density in this period was 1.17–1.2 g/cm^3, which is 0.04–0.96 g/cm^3 less compared to the aftereffect of the first year at the first application.

When irrigated, the effect of phosphogypsum as a chemical ameliorant on the density of the soil composition is more significant, compared to non-irrigated options. Over the years of research, the same trend was observed as in the absence of irrigation (increased density in dry years and the lowest values in the first year of the post-action when repeated application of phosphogypsum). The value of the density in the first year after the effect when phosphogypsum was re-applied was 1.18–1.21 g/cm^3.

The porosity of the soil in the control areas without the phosphogypsum addition and without irrigation varied in the ranges from 50.0 to 50.8 % (Table 4). With irrigation according to the average indicators in all years of the research, the value of the sparability of the arable layer of the soil in the control areas was 47.14 %, and in the absence of irrigation, this indicator was 3.24 % higher. This is explained by the increased corresponding indicators of soil density. Over the years of research, under irrigation conditions, a tendency to decrease sparability was noted, while without irrigation, no clear dynamics were observed, i.e., the values changed randomly (Table 4).

The phosphogypsum addition significantly affected the indicators of soil porosity. An improvement in sparability indicators was observed in all variants of experiments, compared to the control. The best option in the absence of irrigation, as well as in the study of density, turned out to be the option with the phosphogypsum addition in the fall under the main tillage at the rate of 6 t/ha. The best indicators of soil sparability were noted in variants without irrigation when phosphogypsum was re-applied in the first year after the application. Cracking in the first year of the after-effect during repeated application increased by 0.17–0.35 %, compared to the after-effect during the first application of phosphogypsum.

Irrigation did not lead to a drastic change in spariness, and over the years of research, the same trend was observed as in the absence of irrigation. The best value of spariness was observed in the first year after the application of phosphogypsum, which was 49.51–50.2 %.

According to our data, the water permeability of the soil in the control without the phosphogypsum addition was higher in the non-irrigated variants, compared to the irrigated ones (Table 4). The phosphogypsum addition had a significant effect on the increase in water permeability of the soil in all variants of the experiment. When applying phosphogypsum without irrigation, the average indicators for all years of research increased by 2.46–2.54 mm/min. The increase in water permeability occurred in proportion to the increase in the application rate of phosphogypsum. This proves the theory of increasing water permeability of irrigated soils during chemical melioration with calcium-containing meliorants during coagulation of soil colloids with calcium cations. The best indicators of soil permeability were noted in variants without irrigation when phosphogypsum was re-applied in the first year after the application. Water permeability increased by 0.02-0.1 mm/min in the first year of the aftereffect during repeated application, compared to the aftereffect during the first application.

With chemical reclamation and irrigation, a decrease in water permeability was observed in comparison with non-irrigated options. As in the variants without irrigation, according to the years of research, the first year after the effect was the best with repeated application – 1.81–1.9 mm/min. This fact indicates the formation of water-resistant aggregates and a decrease in the mobility of silty particles when adding calcium with phosphogypsum. Due to this, the water resistance of the soil increases, filtration increases, which helps to wash salts from the soil. amelioration, it has acquired the status of good from satisfactory.

Conclusions. The use of phosphogypsum as a chemical ameliorant to prevent degradation processes occurring in ordinary chernozems has a positive effect on the anion-cation composition of the water extract and the degree of soil salinity. According to the "total effect" of toxic ions, the degree of soil salinity changes to a slightly saline type when phosphogypsum is applied at the rate of 3 and 6 t/ha with irrigation.

The increased ameliorative effect of phosphogypsum was observed precisely with irrigation because the sodium-adsorption ratio (SAR) in the third year after the application decreased by 10 % in the variants without irrigation, and with irrigation – by 69 % in relation to the control variants. According to the SAR indicators, the options with the application of phosphogypsum at the rate of 3 and 6 t/ha during irrigation turned out to be the best.

Under irrigation conditions, the improvement of the ecological condition of saline soils was noted when phosphogypsum was applied at the rate of 3 t/ha, which increased the water permeability of the soil by 0.66 mm/min and reduced the number of toxic salts to 0.41 % in the third year after the effect. In non-irrigated conditions, the best option was the phosphogypsum addition in the fall under the main tillage at the rate of 6 t/ha, which increased the water permeability of the soil by 0.68 mm/min and reduced the amount of toxic salts to 0.38% in the third year after the action.

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ВПЛИВ ФОСФОГІПСУ НА СОЛЬОВИЙ СКЛАД ЗАСОЛЕННОГО ГРУНТУ

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Анотація. *Глобальні зміни клімату в багатьох країнах світу призводять до необхідності використання зрошення як рушійного фактору для отримання гарантованих і стабільних врожаїв сільськогосподарських культур. Поливи водою різної якості призводять не лише до підвищення врожайності, а й до зміни сольового складу в ґрунті. Значно швидше відбуваються зміни сольового складу в ґрунті при зрошенні мінералізованою водою, що призводить до накопичення розчинних солей в орному шарі та погіршення складу ґрунтового вбирного комплексу. Накопичення іонів натрію призводить до засолення зрошуваних ґрунтів. Зупинити або призупинити процеси засолення можна шляхом проведенням хімічної меліорації використовуючи кальцієвмісні меліоранти. В якості такого меліоранту в цій роботі запропоновано використання побічного продукту виробництва мінеральних добрив – фосфогіпсу. Він містить значну кількість кальцію (до 95%) та здатний замінити обмінний натрій у ґрунтовому поглинальному комплексі. Наведеними дослідженнями встановлено оптимальні розрахункові норми і строки внесення фосфогіпсу, його вплив на зміну компонентів ґрунтової сольової витяжки. Дослідження проводили на ґрунтах, що тривалий час (понад 50 років) зрошувалися мінералізованою водою з річки Самара (Україна). За кількістю обмінного натрію ґрунти дослідних ділянок належали до малонатрієвих із фізичними ознаками процесів засолення, а за вмістом токсичних солей – до середньозасолених. Для використання фосфогіпсу в ґрунтово-меліоративних умовах північного Степу України розраховані меліоративні, агрономічні та екологічно безпечні норми внесення навесні та восени. Схема дослідів передбачала варіанти зі зрошенням шляхом дощування і без поливу. Склад водної витяжки визначали за показниками вмісту аніонів-катіонів. Під час досліджень спостерігали поступове зменшення кількості сульфатів: на 1,5 % на другий рік після внесення в ґрунт, та на 7,5 % на третій рік після внесення фосфогіпсу. На зрошуваних площах, де вносився фосфогіпс, кількість гідрокарбонатів зменшувалася, а на ділянках, де зрошення не проводили, спостерігали підвищення їх вмісту. Варіанти на поливі характеризувались значним збільшенням вмісту іонів хлору, що пояснюється надходженням цих іонів виключно з поливною водою. Ступінь солоності визначали за pH і коефіцієнтом адсорбції натрію (SAR). За цими показниками встановлено, що у всіх варіантах дослідів ґрунти виявилися слабозасоленими. У результаті проведених багаторічних досліджень відзначено позитивний вплив фосфогіпсу як меліоранта на аніонно-катіонний склад водної витяжки та ступінь засолення ґрунтів, що поливали мінералізованою водою протягом тривалого часу. За аніонним складом хімічний склад ґрунтів на дослідних ділянках у варіантах із внесенням фосфогіпсу і вегетаційними поливами та на ділянках без зрошення був* *сульфатним, а на контрольних ділянках (без внесення фосфогіпсу та без поливів) – содово-сульфатним. Хімічний склад ґрунтів на дослідних ділянках за катіонним складом був натрієвим у всіх варіантах дослідів. За натрій-адсорбційним коефіцієнтом (SAR) ступінь засолення ґрунту відноситься до слабозасоленого типу, тоді як на контрольних ділянках без фосфогіпсу залишався середній тип засолення.*

Ключові слова: *аніонно-катіонний склад, водна витяжка ґрунту, фосфогіпс, коефіцієнт адсорбції натрію*