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Influence of zeolite and zeolite-containing fertilizers on the crop capacity and grain quality of winter wheat

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Abstract. The study is dedicated to investigating the effects of zeolite and zeolite-based fertilizers enriched with amino acids and urea on the yield and grain quality of winter wheat. Experimental research was conducted at the P.A. Stolypin Ulyanovsk State Agricultural University. Field trials involved seven variants of soil treatment: a control plot, application of zeolite at doses of 250 kg/ha and 500 kg/ha, usage of zeolite enriched with amino acids at the same two concentrations, and analogous application of zeolite supplemented with urea. The soil of the experimental site represents a typical medium-powerful medium-loamy chernozem. Trials were carried out on crops of the "Saratovskaya 17" winter wheat variety. It was found that winter wheat yields increased by 0.22 and 0.88 t/ha on average over three years with the application of zeolite as a soil fertilizer (4.26 t/ha in the control option). The application of zeolite enriched with amino acids at doses of 250 and 500 t/ha secured the largest increase in the grain yield, 0.72 and 0.88 t/ha. It was also observed that this option improved grain quality and its environmental safety.

1 Introduction

One of the promising areas of the nutritional regime optimization of soils during the cultivation of crops is the use of silicon (silicate) fertilizers, including natural silicon-containing rocks such as diatomites, zeolites, bentonites, etc. A number of publications demonstrated the effectiveness of siliceous rocks, including zeolites, in the production of agricultural produce [1-5].

It should be noted that the natural high-siliceous rocks mentioned above possess a number of properties that are important from agronomic perspective. In particular, the crystal structure of zeolites is unique. Their crystal lattice is made up of four-, five-, six-component, and even more complex rings formed by silicon-oxygen tetrahedra (Fig. 1), owing to which a system of pores is formed within the crystalline space, interconnected with each other and

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the surrounding environment. These pores contain cations of calcium, sodium, potassium, magnesium, and sometimes barium, strontium, and lithium, as well as molecules of "zeolitic" water, which can be exchanged for other cations or molecules large enough to penetrate the entrance pores. This structural feature of zeolites allows them to be used to create effective, environmentally friendly fertilizers that best meet the needs of crops by incorporating certain elements (compounds).

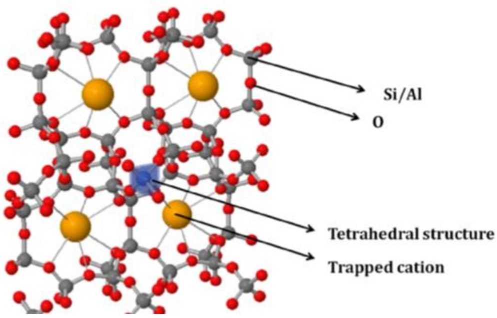

Fig. 1. Zeolite tetrahedral structure (The International Zeolite Association (IZA))

It should also be pointed out that siliceous rocks with high silicon content serve primarily as silicon fertilizers. Silicon is equally important as nitrogen, phosphorus, and potassium in terms of nutrition; it plays a unique role both in maintaining soil fertility and strengthening the immune system of cultivated plants [4, 6, 7, 8].

Therefore, the aim of our research was to evaluate the effectiveness of a high-siliceous rock—zeolite—and fertilizers based on it in winter wheat cultivation in conditions of the forest-steppe of the Middle Volga region. (The International Zeolite Association (IZA)).

2 Materials and methods

The studies were conducted on the experimental field of P.A. Stolypin Ulyanovsk State Agrarian University in 2020-2023. The field experiment included 7 options: 1. Control (natural fertility - C); 2. Zeolite, 250 kg/ha (Z 250); 3. Zeolite, 500 kg/ha (Z 500); 4. Zeolite enriched with amino acids, 250 kg/ha (ZA 250); 5. Zeolite enriched with amino acids, 500 kg/ha (ZA 500); 6. Zeolite enriched with urea, 250 kg/ha (ZU 250); 7. Zeolite enriched with urea, 500 kg/ha (ZU 500). The experiment was carried out in four replicates with a randomized arrangement of plots. The sown area of the plots was 40 m^2 (4 x 10 m^2), and the registered area was 20 m^2 (2 x 10 m^2).

The experimental field's soil was characterized as typical medium-thick, medium-loamy black earth, featuring 4.6% humus content within the plough layer, along with available phosphorus (P_2O_5) at 155 mg/kg and potassium (K_2O) at 176 mg/kg, all set against a soil solution pH level of 6.7.

Meteorological conditions during the field trials varied in both temperature and precipitation. The hydrothermal coefficient (HTC), defined as the ratio of precipitation during the growing season to the sum of temperatures, reflects the weather conditions during these years. It was 0.78 in 2021, 0.84 in 2022, and 0.44 in 2023. Consequently, 2022 was the most favorable year in this regard.

The experimental crop was winter wheat (Triticum aestivum L.), the variety "Saratovskaya 17". This variety shows a good combination of high yields with good quality indicators.

Experimental fertilizers were zeolite from the Maina deposit in the Ulyanovsk region, the chemical composition of which is shown in Figure 2; the amino acid composition used to enrich zeolite is shown in Figure 3. Fertilizers were applied while cultivating the field before sowing winter wheat.

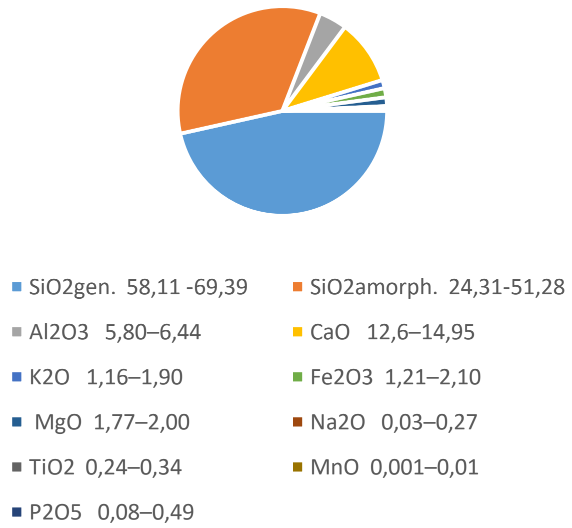

Fig. 2. Chemical composition of zeolite, %

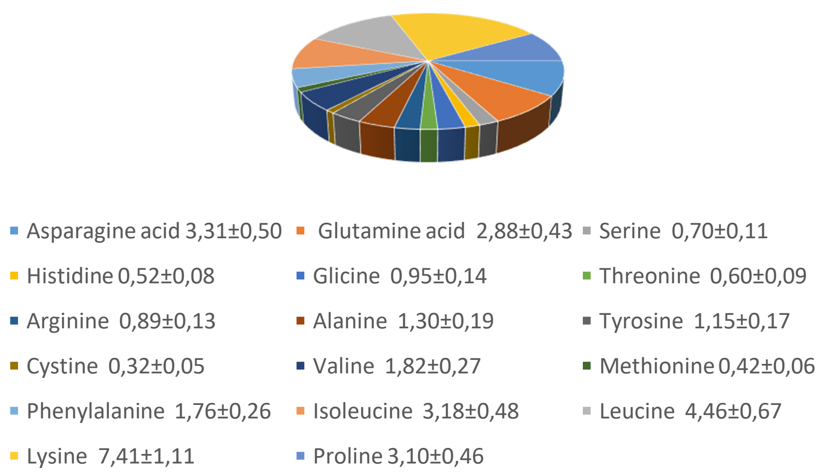

Fig. 3. Amino acid composition, %

Determination methods: in soil samples – exchangeable acidity (pH_{KCl}) GOST (state standard) 26483-85, mobile forms of phosphorus (P_2O_5) and potassium (K_2O) GOST 26204-

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91, humus GOST 26213-91; in grain – phosphorus GOST 26657-97, total potassium GOST 30504-97, protein GOST 10846-91, gluten GOST 10846-74.

Processing of statistical data derived from the research outcomes was performed using methods of variance analysis and correlation-regression analysis, utilizing Microsoft Excel version 2019 and the specialized software package Statistik C-1.

3 Results

Crop yields measure the effectiveness of any agro-technical practices used, including plant nutrition. Fertilizer application is a key factor influencing both soil fertility and crop yields. Assessment of the effect of zeolite-containing fertilizers on winter wheat yield is presented in Table 1.

Table 1. Dependence of winter wheat grain yield on types of applied fertilizers, t/ha

Option	2021	2022	2023	Average for 3 years	Deviation from control, ±	
					t/ha	%
Control	3,37	5,27	4,14	4,26	-	-
Z 250	3,61	5,44	4,38	4,48	+0,22	5
Z 500	3,77	5,86	4,48	4,70	+0,44	10
Z+A 250	4,04	6,06	4,84	4,98	+0,72	17
Z+A 500	4,12	6,29	5,02	5,14	+0,88	21
Z+U 250	4,08	5,99	4,57	4,88	+0,62	15
Z+U 500	4,17	6,18	4,64	5,00	+0,74	17
LSD 05	0,13	0,14	0,13			

Plant nutrition optimization contributes to an increase not only in the crop yield but also in product quality. Zeolite and zeolite-containing fertilizers, which significantly improve the physical and chemical properties of the soil, have had a positive effect on the nutritional regime of the soil and, consequently, on product quality (Fig. 4).

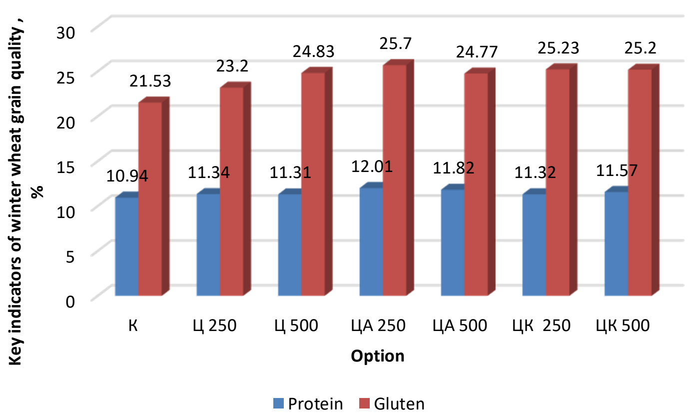

Fig. 4. Key quality indicators for winter wheat grain, % (2021-2023)

At present the concept of product quality necessarily comprises its environmental safety. The heavy metal content of winter wheat grain is given in Table 2.

Table 2. Changes in heavy metals content in winter wheat grain when using zeolite-based fertilizers, mg/kg (2021-2023)

Option	Zn	Cu	Pb	Cd	Ni
Control	19,7	1,9	0,33	0,030	0,47
Z 250	18,2	1,7	0,15	0,018	0,31
Z 500	17,1	1,7	0,23	0,018	0,33
Z+A 250	16,7	1,6	0,19	0,016	0,30
Z+A 500	14,8	1,7	0,24	0,015	0,31
Z+U 250	17,8	1,8	0,17	0,018	0,39
Z+U 500	18,6	1,8	0,18	0,022	0,31
LSD_{05}	1,3	0,07	0,05	0,002	0,02
MPC*	50	10	0,50	0,10	0,50

* Sanitary regulations and norms 42-123-4089-85 "Maximum permissible concentrations of heavy metals and arsenic in food raw materials and food products"

4 Discussion

Upon analyzing the data presented in Table 1, one cannot help but notice the pronounced interannual variability in winter wheat yields, ranging from 3.27 tons per hectare in 2021 to 5.27 tons per hectare in 2022. This fluctuation reflects the distinct features of the regional agroclimatic zone, particularly its susceptibility to adverse meteorological events. The forest-steppe belt of the Middle Volga region exhibits inconsistent precipitation patterns during the critical phases of plant growth, including episodes of severe drought and sporadic heavy rains. Nevertheless, the inherent qualities of chernozem soils enable robust winter wheat harvests during favorable climatic years, typically yielding around 5-6 tons per hectare. During our 2022 trials, the unfertilized control group achieved a relatively high grain yield of 5.27 tons per hectare, primarily attributable to superior overwintering conditions, adequate soil moisture availability, and conducive thermal regimes throughout the vegetation cycle.

Employment of pure zeolite as a soil amendment had a profound impact on grain productivity, resulting in average increments of 0.22 to 0.44 tons per hectare over a three-year span, contingent upon the quantity administered. Our findings reveal that doubling the zeolite application rate (i.e., 250 vs. 500 kg per hectare) proportionately amplified yield enhancements, underscoring the crop's notable sensitivity to silicon-derived nutrients. Moreover, our analyses highlight the presence of a silicon deficit (manifested as monosilicic acid insufficiency) in the experimental field's soil composition.

The application of fertilizer based on zeolite in winter wheat cultivation technologies contributed to a significant increase in its yield. Specifically, the grain yield increased by between 0.62 tons/ha when using zeolite enriched with Urea at a dose of 250 kg/ha, and up to 0.88 tons/ha when applying zeolite saturated with amino acids at a dosage of 500 kg/ha. The latter was due to the complex positive effects of zeolite and zeolite-based fertilizers on soil properties and the soil-plant system. Our research demonstrated that the application of these fertilizers improved the physicochemical properties of the topsoil layer, ensuring optimal moisture retention and creating conditions necessary for the full-fledged growth of winter wheat. Due to the introduction of zeolitic formulations, microbial activity in the soil increased, leading to enhanced availability of essential nutrients for plants. Over the course of three years, compared to the control, the concentration of mineral nitrogen in the root-inhabited soil layer (depth 0–30 cm) rose by 1.9–3.8 mg/kg, the amount of available phosphorus (P_2O_5) increased by 2–17 mg/kg, and reserves of accessible potassium (K_2O) grew by 6–15 mg/kg.

Similar results on the influence of siliceous rocks on the soil-plant system were reported in [1,9,10].

Protein content and gluten levels play a decisive role in determining baking properties of flour produced from wheat grains. According to GOST 9353-90, protein content in wheat grains should range from 11% to 17%. In accordance with this standard, minimum gluten content requirements are distributed as follows: premium class must have no less than 36%; first-class — not lower than 32%; second-class — at least 28%; third-class — from 23%; fourth-class — minimum 18%.

Grain quality testing in the experiments showed that the use of pure zeolite in the winter wheat cultivation technology had no effect on protein content, but significantly increased the gluten content. Improving the nutritional regime of the soil through the application of zeolite with nitrogen-containing compounds (amino acids, urea) increased grain protein content by 0.38-1.07% and gluten content by 3.24-4.17% (absolute values). The best indicators for protein and gluten content in wheat grain were achieved with the use of zeolite enriched with amino acids at a dose of 250 kg/ha: 12.01% and 25.70%.

When producing agricultural products, especially crops, environmental safety is paramount. In this respect, one of the major problems is the contamination of soils and crops with heavy metals. Therefore, monitoring their content in soils and plant products is mandatory nowadays, and is carried out by the agrochemical service of the country. Based on our research, the content of heavy metals (zinc, copper, lead, cadmium, nickel) in winter wheat grain cultivated under experimental conditions remained within established norms and did not exceed the maximum permissible concentration. At the same time, the use of zeolite and zeolite-based fertilizers led to a decrease in the share of these metals in the grain: copper content decreased by 11-16%, zinc by 6-25%, nickel by 11-36%, lead by 27-64%, and cadmium by 27-50% (the extent of reduction depended on the dose of zeolite and its enrichment method using amino acids or urea). The studies undertaken by J. Bhat (2019), V. Jakkula (2018), and K. Ramesh (2011) testify to the potential for reducing the uptake of heavy metals by plants from soil through the use of zeolite-based fertilizers. The mechanism for reducing the accumulation of heavy metals in crops is due to a decrease in their mobility in soils in the presence of silicon. Monosilicic acid is known to form poorly soluble silicates with heavy metals [11].

5 Conclusions

1. The use of zeolite and zeolite-based fertilizers in the cultivation of winter wheat allowed us to increase its productivity by 0.22–0.88 tons per hectare. The greatest increase in grain yield, ranging from 0.72 to 0.88 tons per hectare, was observed when zeolite enriched with amino acids was applied to the soil at doses of 250 and 500 kilograms per hectare respectively.
2. Zeolite and zeolite-based fertilizers give an opportunity to increase the protein and gluten content of winter wheat grain: from 10.94% in the control group to 12.01% when applied at a dose of 250 kg/ha, and gluten content from 21.53 to 25.70%.
3. The use of zeolite and zeolite-containing fertilizers enhances the environmental safety of products through reduced accumulation of heavy metals: copper uptake decreases by 11–

16%, zinc by 6–25%, with the degree of reduction depending on the dosage and methods of enriching zeolite with amino acids and urea.

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