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BENEFICIAL EFFECTS OF SILICON FERTILIZERS ON INDICATORS OF SEED GERMINATION, GRAIN YIELD OF BARLEY AND SOYBEAN AND SILAGE CORN BIOMASS

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Abstract: The aim of the study was to determine the optimal doses and methods of the application of silicon fertilizer in barley, silage corn, and soybean under the climatic conditions of Ukraine. A series of laboratory and field experiments were carried out, as along with statistical and analytic data processing. The small-plot field experiment was conducted on chernozem podzolic soil at the NSC "Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky" (Kharkiv region, Forest-Steppe of Ukraine). The laboratory experiments were set up in Petri dishes using a preparative form of different concentrations (0%, 0.5%, 0.75% and 1.0%) of potassium silicate for their assessment of the germination indicators of barley and corn seeds. The significant stimulating effect of potassium silicate on the germination capacity and germination energy of barley and corn seeds was shown, and the optimal concentration of the solution for pre-sowing seed treatment was established. A high positive correlation was determined between the amount of SiO_2 application and the yield of the studied crops ($P < 0.01$; $R = 0,7479\text{-}0,8682$). The optimal levels of the pre-sowing application of SiO_2 into the soil were established to obtain maximum crop yields on chernozem podzolic soil (105 kg SiO_2 ha^{-1} for barley, 92 kg SiO_2ha^{-1} for silage corn, and 76 kg SiO_2ha^{-1} for soybean). Also, for each of the studied crops, the most optimal methods of the application of silicon fertilizers were determined, which will improve their productivity on chernozem soils.

Key words: silicon, plant nutrition, crop productivity, mineral fertilizer.

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Introduction

Degradation of soil cover, environmental pollution, decline in the quality of agricultural products, increased frequency of extreme weather conditions, and deficiency of energy resources require the widespread introduction of new, environmentally adaptable, and at the same time, highly efficient methods of farming. Much of the degradation of agricultural land and the decline in the quality of agricultural products is associated with unbalanced fertilization and plant nutrition (Aristarkhov and Mineev, 2000). However, in comparison with the deep theoretical substantiation of the optimization of nitrogen-phosphorus-potassium nutrition in the soil-plant continuum, the issues of mesoelements (S, Si, Mg) have received much less attention in agrochemical studies. Nevertheless, it is well known that all elements of mineral nutrition are closely related to each other through participation in common processes, but the role of each of them is strictly specific.

The biological value of nutrients such as silicon (Si) has been known for over 150 years, but its role in plant nutrition, especially under stress conditions, has only been studied carefully in recent decades (Liang et al., 2015). Less interest among researchers could be explained by the fact that silicon does not belong to strictly essential elements for plants, since they can perform their life cycles without it (Epstein, 1999; Liang et al., 2015). In addition, Si is the second most abundant element in the Earth's crust and accounts for 27.7% of the total soil mass. Its total content in clay soils ranges from 200 to 300 g per kg, in sandy soils – 450–480 g per kg (Haynes, 2014; Liang et al., 2015; Meharg and Meharg, 2015). However, plants absorb only soluble forms of Si – the monomer of silicic acid, and its anions (Ma et al., 2001). Silicon is present in plants in amounts equivalent to those macronutrient elements such as calcium, magnesium, and phosphorus (Epstein, 1999), and in grasses often at higher levels than any other inorganic constituent, and the removal of this element by the crop yield ranges from 20 to 700 kg per ha, which is close to removing nitrogen, phosphorus, and potassium (Bocharnikova and Matichenkov, 2012). Silicon is a structure-forming element in soil; therefore, its constant removal leads to a deficit that reduces the natural protective properties of agricultural plants (Bocharnikova and Matichenkov, 2012).

Numerous studies show that Si improves the growth, yields and quality of crops as well as photosynthesis, nitrogen and phosphorus utilization in soil (Liang et al., 2007, 2015; Cooke and Leishman, 2011; Guntzer et al., 2012; Van Bockhaven et al., 2013; Cuong et al., 2017; Jiang-xue Long et al., 2018). The role of silicon is especially important in increasing plant resistance to abiotic and biotic stresses; therefore, Fauteux et al. (2006), Chain et al. (2009), Nwugo and Huerta (2011), Epstein (2009), Van Bockhaven et al. (2013) believe that its effectiveness is limited exclusively by stressful conditions. The optimization of silicon nutrition is considered to help plants adapt to drought, high temperatures, frost, radiation, ultraviolet radiation, and chemical stresses caused by salinity, metal toxicity, nutrient imbalances, etc. (Epstein, 1994; Hattori et al., 2005; Ma, 2004). However, long-term studies have also proved the effectiveness of silicon fertilization under non-stressful conditions (Tamai and Ma, 2008; Detmann et al., 2012, 2013). The use of silicon as a fertilizer helps to improve the yield components of wheat, rice, soybean, corn, rapeseed, and sugar beet by improving photosynthetic activity, increasing the efficiency of using macronutrients and soil moisture (Maghsoudi et al., 2015; Amin et al., 2016; Artyszak et al., 2016; Artyszak and Kuci'nska, 2016; White et al., 2017; Walsh et al., 2018). It is also important that the use of silicon is safe for the natural environment, and that it can be used in organic farming, which has become highly important.

So, we can assume that silicon has the characteristics of an essential nutrient for plant growth and, according to Ma et al. (2001), it can be included in the list of the main elements for increasing the productivity of grain crops. In 1999, the first scientific conference on "Silicon and Agriculture" was held in the United States and this gave an impetus for the global fertilizer market and agricultural production in general to pay attention to silicon-containing fertilizers (Jiang-xue Long et al., 2018).

Since the use of silicon fertilizers significantly improves the growth and development of agricultural crops, increases the level of their productivity, and improves the quality of the products obtained under stressful conditions, it is relevant to determine the optimal doses and methods of applying silicon fertilizers in the soil and climatic conditions of Ukraine. It is also important to clarify the possibility of their combination with mineral fertilizers for crops that occupy an important place in the structure of sown areas in Ukraine. The aim of this study was to determine the optimal doses and methods of applying silicon fertilizers under barley, corn and soybean in the soil and climatic conditions of Ukraine.

Material and Methods

The studies were carried out with a preparative form of potassium silicate with a mass fraction of silicon dioxide – 21.3% and potassium oxide – 8.3% under the conditions of laboratory experiments and a small-plot field experiment.

The aim of the laboratory experiments was to determine the optimal concentration of the working solution of potassium silicate for pre-sowing seed treatment. Laboratory studies assessed the effect of potassium silicate on the germination of barley and corn seeds according to the following indicators: germination capacity, germination energy, and germination synchronization index. The course of this experiment included: 100 seeds of barley and corn, previously kept for 8 hours in solutions of potassium silicate at four concentrations (0%, 0.5%, 0.75%, and 1.0%) with four replicates laid out on the filter paper moistened with distilled water in the Petri dishes. In the control variant, seeds were soaked in distilled water. The dishes were kept in a lighted laboratory cabinet at a constant air temperature of 25°C for 7 days and controlled by the humidity of the filter paper. An assessment of the germination energy (GE) was carried out on day 4, and of the germination capacity (GC) on day 7 following the placement of seeds on the filter paper in the Petri dishes. The germination synchronization index (GSI) was determined according to a modified methodological approach by Primack (1980) – and calculated using the formula:

$$GSI = \frac{GC}{D} \tag{1}$$

GSI – germination synchronization index, %;
GC – germination capacity, %;
D – number of days of germination.

Additionally, the primary root length was measured in 10 normal seedlings randomly obtained after the germination capacity calculation (on the 7th day).

The field experiment was conducted in 2020 at the experimental site of the NSC "Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky" (State Enterprise "Experimental Farm Grakivske" Kharkiv district of Kharkiv region, Ukraine, geographical coordinates: 49˚46′N lat., 39˚40′ E long). The experiments were established on chernozem podzolic heavy loamic soil (Luvic Chernozem according to WRB) with the following characteristics: pH_{KCl} – 6.0; organic carbon content determined by the Tyurin method – 2.8%; the content of mobile phosphorus and potassium determined in acetic acid extract – 138 and 90 mg kg^{-1}, respectively. The sum of precipitation during the research period was properly distributed, and it amounted to 417 mm from April to September (Table 1).

Table 1. Weather conditions during the growing season of 2020.

Months	Air temperature,°C		Precipitation, mm	
	study period	average annual data	study period	average annual data
April	12.1	11.0	46.0	34.5
May	15.4	17.9	148.0	38.9
June	20.1	21.9	54.0	42.2
July	22.6	21.9	92.0	50.2
August	22.3	20.3	63.0	42.0
September	14.0	16.0	14.0	19.0
April–September	17.75	18.2	417.0	226.8

In the field experiment, three agricultural crops were grown according to the technology traditional for the forest-steppe zone of Ukraine. Spring barley variety Helios was sown on April 5, 2020, and the crop was harvested on July 3, 2020. The seed rate was 450 seeds/m^2, and the row spacing was 15 cm. Silage corn hybrid DN Anshlah (FAO 420) was sown on April 27, 2020, and harvested on August 20, 2020. The seed rate was 80 thousand seeds/ha, and the row spacing was 70 cm. Soybean variety Baika was sown on May 7, 2020, and harvested on September 18, 2020. The seed rate was 750 thousand seeds/ha, and the row spacing was 15 cm.

The scheme of field experiments for each crop included 5 treatments:

1) Basal fertilization (control) (different for each crop);

2) Basal fertilization + potassium silicate (banding of 60 kg SiO_2 ha $^{-1}$);

3) Basal fertilization + potassium silicate (banding 120 kg SiO_2 ha^{-1});

4) Basal fertilization + potassium silicate (banding 60 kg SiO_2 ha^{-1}) + foliar application (30 kg SiO_2 ha^{-1});

5) Basal fertilization + foliar application of 30 kg SiO_2 ha^{-1}.

The experiments were conducted as small plot research trials with six replications in a completely randomized design. The rate of the application of the basal fertilization for barley and corn was $N_{40}P_{40}K_{40}$, and for soybean – $N_{90}P_{60}K_{60}$. The basal fertilization was applied in the form of nitroammophoska (16:16:16) and ammonium nitrate broadcast under pre-sowing cultivation, potassium silicate – during sowing of agricultural crops into the soil locally in the band at a distance of 3–4 cm to the side and 10–12 cm below the sowing row. The foliar applications of potassium silicate were made to spring barley in the tillering phase, to corn – in the phase of 6–8 leaves, to soybean – in the phase of the third to fifth nodes (V3 to V5).

Soybean grain yield was calculated at 13–14% moisture content and barley grain yield at 14–17% moisture content. Silage corn was harvested at milk-wax maturity (biomass weight was measured).

All the data were analyzed using STATISTICA 13.5.0.17. The least significant difference (LSD) test for treatment parameters was done after performing ANOVA, at the $P<0.05$ significance level. Quadratic regression equations were also developed to describe the performance of silicon fertilizers for each crop.

Results and Discussion

Seed treatment with a silicate solution provides plants with additional silicon at the seed germination phase. Kozlov et al. (2015) found that the change in the quality indicators of grain crops is significantly affected by the dose of silicon, in particular, the concentration of the working solution in seed treatment.

The results of our study showed that the indicators of germination capacity and germination energy of barley and corn seeds were higher in all seed treatments with potassium silicate solution than in the control, except for germination energy in barley (Table 2). However, no significance was observed in 1.0% working solution treatment compared to the control. Increasing the concentration of potassium silicate solution above 0.75% was not effective for the pre-sowing seed treatment. The treatment with a 0.5% potassium silicate solution also did not differ significantly from the control, which indicates an insufficient stimulating effect of this concentration.

Table 2. Parameters of germination of seeds treated with a potassium silicate solution of various concentrations (laboratory experiment).

Experiment options (concentration of potassium silicate solution)	Germination capacity (%)	Germination energy (%)	Germination synchronization index (%)	Root length (cm)
Barley				
Control (without treatment)	85.0	85.0	12.1	8.4
0.5%	90.0	85.0	12.9	8.8
0.75%	100.0	95.0	14.3	9.4
1.0%	87.5	85.0	12.5	8.7
SE	4.9	3.1	0.7	0.1
LSD$(p \leq 0.05)$	15.6	10.1	2.2	0.3
Corn				
Control (without treatment)	87.5	87.5	12.5	8.8
0.5%	91.6	91.6	13.1	9.2
0.75%	100.0	100.0	14.2	10.5
1.0%	95.8	87.5	13.7	9.7
SE	3.4	3.4	0.5	0.2
LSD$(p \leq 0.05)$	10.8	10.8	1.6	0.6

The highest values of germination capacity and germination energy, which were 10–15% higher for barley seeds and 12.5% higher for corn seeds compared to the control, were determined when seeds were treated with a 0.75% potassium silicate solution. The changes in the germination synchronization index of barley and corn seeds, depending on their treatment with a potassium silicate solution at various concentrations, had the same character as for the indicators of germination and germination energy. Therefore, increasing the concentration of the working solution to 1.0% of potassium silicate did not improve all indicators of seed germination.

Germination and germination energy are the main indicators of seed quality that directly affect the yield of agricultural crops and are especially important under conditions of the increasing frequency of droughts and other abiotic stresses associated with climate change (Pati et al., 2016).

Another indicator of the effect of potassium silicate on seed germination, which was determined in a laboratory experiment, is root length. The optimization of Si nutrition increases root mass and volume and increases total and adsorbing surfaces (Matichenkov, 1996). Since the root system is responsible for the absorption and transport of nutrients and water to plants, the normal growth and development of the underground part of the plant are extremely important for the further formation of a crop. The length of corn roots on the 7th day of seed germination under all treatments ranged from 8.8 cm to 10.5 cm, and for barley this indicator was 8.4–9.4 cm. Root length of corn was increased by 2.6% and in barley by 9.4% compared to the control. The most pronounced beneficial effect was obtained when seeds were treated with a potassium silicate solution at a concentration of 0.75%.

The positive effect of treating corn and barley seeds with potassium silicate solutions on their germination indicators, confirmed by the data in Table 2, would contribute to the formation of a developed root system of the plants and to an increase in the water content in the tissues in case of soil water deficit in spring. Numerous studies show that monosilicic acids increase the germination of cereal seeds, accelerate the formation of rice, and promote the ripening of citrus fruits (Savant et al., 1997; Matichenkov et al., 1999). The stimulation of the growth of primary roots of crops discovered correlates with information on the optimization of silicon nutrition of plants, which leads to an increase in the total mass of roots (Matichenkov, 1996), their branching (Matichenkov et al., 1999), the total and working adsorbing surface (Kudinova, 1975), and increased root respiration (Yamaguchi et al., 1995).

In the field experiment, in order to determine the effect of silicon fertilizer on the productivity of barley, soybean and silage corn, potassium silicate was applied locally into the soil and foliarly. The use of silicon fertilizer significantly influenced the productivity of spring barley (Table 3). In all studied treatments, a significant increase in the grain yield and total aboveground biomass relative to control was obtained.

The increase in total barley biomass ranged from 20% to 53% while the percentage of grain in total biomass was 48.2–51.7. The highest increase in both grain yield and aboveground biomass was obtained under treatment with 120 kg SiO_2/ha. Surprisingly, under treatment with combined silicon soil and foliar application, both grain yield and aboveground biomass were significantly lower in comparison to the treatment with corresponding soil fertilization (Table 3).

In our opinion, an increase in the total biomass of barley plants, first of all, may be due to an increase in the growth of the root system at the initial stages of plant ontogenesis. In particular, the use of silicon-containing fertilizers for barley in the experiments of Balakhnina et al. (2012) and Włodarczyk et al. (2019) stimulated the growth of shoots and roots of barley, leading to a significant increase in biomass under optimal growing conditions. The application of readily soluble silicon increases the availability of Si in the soil and also stimulates the absorption of more Si from the soil solution (Pati et al., 2016). As noted by Ahmad et al. (2016), the addition of potassium metasilicate (K_2SiO_3) to the soil promotes the concentration of K^+ ions in plant shoots, which helps to maintain water potential under drought conditions.

Table 3. The effect of potassium silicate soil and foliar application on the aboveground biomass and grain yield of spring barley.

Field experiment treatments	Aboveground biomass, (t ha^{-1})	Grain yield, (t ha^{-1})	Percentage of grain from biomass yield (%)
Basal fertilization (control)	4.50	2.52	56.0
Basal fertilization + potassium silicate (banding 60 kg SiO_2 ha $^{-1}$)	6.60	3.18	48.2
Basal fertilization + potassium silicate (banding 120 kg SiO_2 ha $^{-1}$)	6.90	3.40	50.7
Basal fertilization + potassium silicate banding (60 kg SiO_2 ha $^{-1}$) + foliar application (30 kg SiO_2 ha $^{-1}$)	5.69	2.94	51.7
Basal fertilization + foliar application (30 kg SiO_2 ha $^{-1}$)	5.40	2.68	49.6
SE	0.72	0.31	-
LSD($p \leq 0.05$)	0.19	0.10	-

Basal fertilization (40 kg N ha^{-1} + 40 kg P_2O_5 ha^{-1} + 40 kg K_2O ha^{-1}); SE, standard error.

Based on the experimental data obtained, a quadratic regression equation was developed ($y = 2.343+0.021*x-0.0001*x^2$, P<0.01), where the top of the curve with an abscissa value of 105 kg ha^{-1} was the highest point on the quadratic function graph (Figure 1). This value can be considered as the optimal level of the potassium silicate application rate, which provided the highest grain yield of 3.44 t ha^{-1}.

It should be noted that, in addition to the direct effect of silicon on the plant organism, an increase in the yield of agricultural crops may be due to its indirect effect on the improvement of phosphorus nutrition of plants. A solution of silicic acid can displace phosphorus from sparingly soluble phosphates that are not available to plants, and this leads to an increase in the concentration of phosphate ions in the soil solution. In addition, the silica hydrogel can adsorb phosphorus ions contained in the soil solution, thereby preventing the chemical binding of phosphate ions by the soil (Cuong et al., 2017).

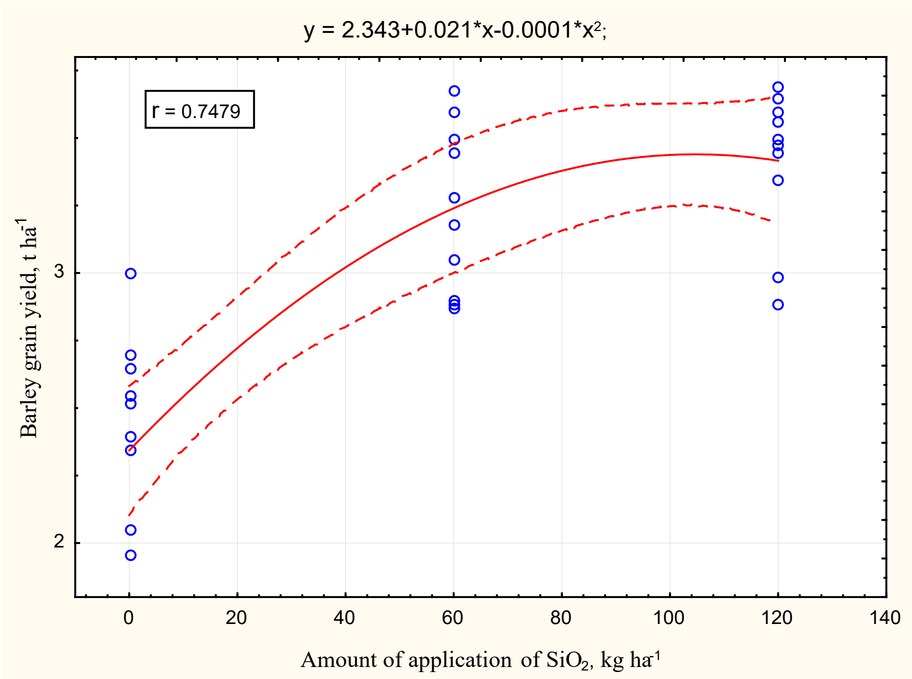


Figure1. The effectiveness of silicon fertilizers for spring barley.

Field studies have also proven the beneficial effects of potassium silicate on silage corn and soybean yields. In all treatments with silicon fertilizer, significant increases in yield were obtained compared to the control: for silage corn – from 16% to 57.3%, for soybean – from 54% to 138% (Table 4). Treatments with 120 kg SiO_2 ha^{-1} and combined potassium silicate soil and foliar application gave the highest increase in the biomass of corn and barley grain yield, respectively.

Quadratic regression models can be used to determine the optimal levels of silicon fertilization. The maximum of the quadratic function of the dependence of the silage corn biomass on the SiO_2 dose was 92 kg SiO_2ha^{-1} (Figure 2A), while the maximum of the quadratic function for soybean was 76 kg SiO_2ha^{-1} (Figure 2B). At these levels of potassium silicate application, the silage corn biomass was 36.3 t ha^{-1}, and gain yield of soybean – 2.4 t ha^{-1}. A further increase in the SiO_2 dose is not justified.

At the same time, the combined soil and foliar application of silicon fertilizers in soybean proved to be more effective than soil application only, which made it possible to obtain the maximum payback of 1 kg SiO_2 by grain yield (Table 4).

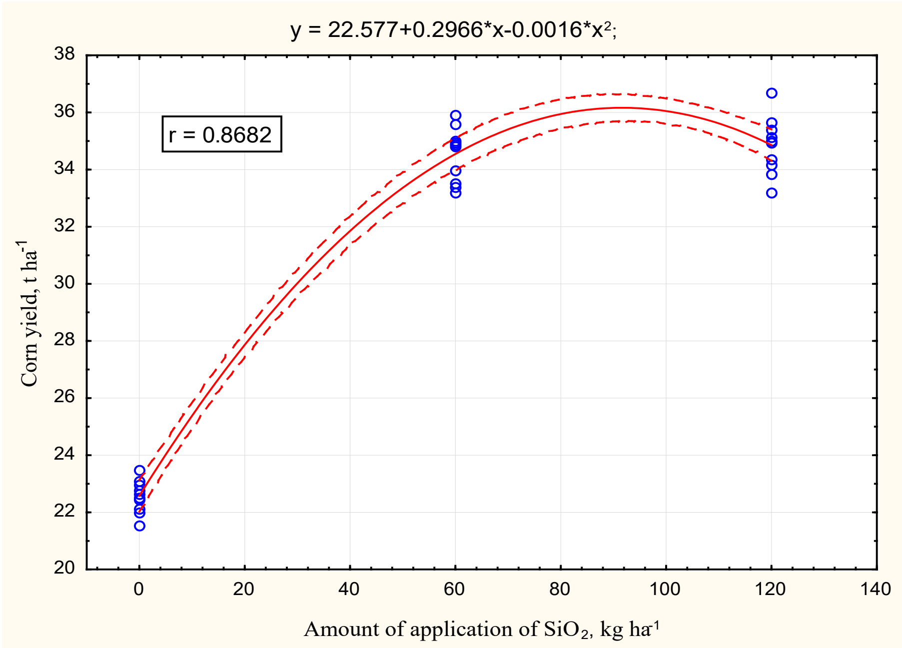
Table 4. The effect of potassium silicate soil and foliar application on the biomass of silage corn and the grain yield of soybean.

Field experiment treatments	Silage corn		Soybean	
	Yield of silage biomass, t ha^{-1}	Payback of 1 kg of active substance potassium silicate by 1 centner of yield	Grain yield, t ha^{-1}	Payback of 1 kg of active substance potassium silicate by 1 centner of yield
Basal fertilization (control)	22.53	-	1.33	-
Basal fertilization + potassium silicate (banding 60 kg SiO_2 ha $^{-1}$)	33.24	1.78	2.17	0.13
Basal fertilization + potassium silicate (banding 120 kg SiO_2 ha $^{-1}$)	35.40	1.08	2.43	0.13
Basal fertilization + potassium silicate banding (60 kg SiO_2 ha $^{-1}$) + foliar application (30 kg SiO_2 ha $^{-1}$)	30.71	0.91	3.10	0.20
Basal fertilization + foliar application (30 kg SiO_2 ha $^{-1}$)	26.12	1.2	2.01	0.23
LSD($p \leq 0.05$)	5.87	-	0.64	-

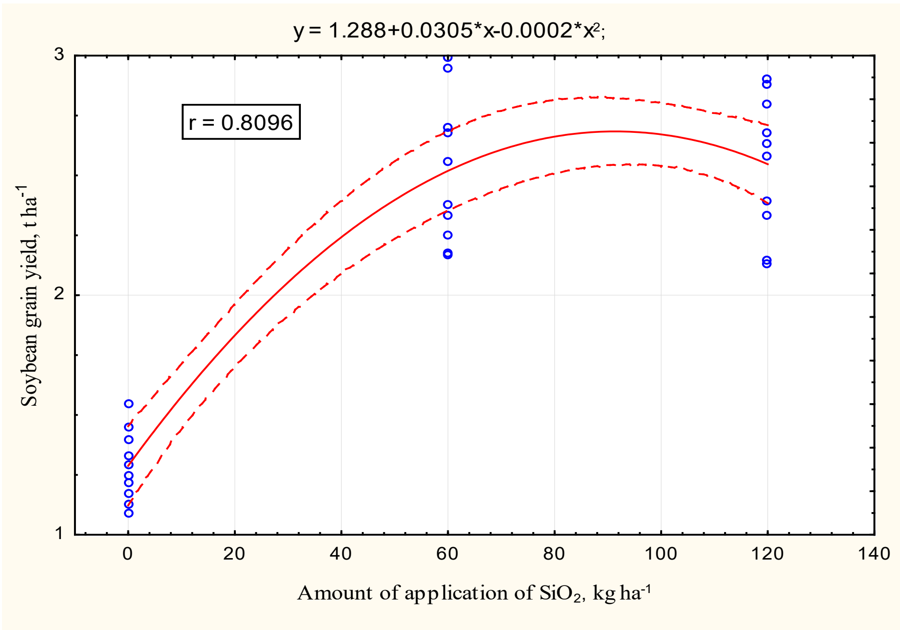
Basal fertilization: for corn – 40 kg N ha^{-1} + 40 kg P_2O_5 ha^{-1} + 40 kg K_2O ha^{-1}; for soybean – 90 kg N ha^{-1}+ 60 kg P_2O_5 ha^{-1} + 60 kg K_2O ha^{-1}; SE, standard error.

A little-studied aspect of the effect of silicon fertilizers on plant growth and development is the effective combination with optimal doses of NPK. According to the results of Jawahar et al. (2017), when growing corn, it was better to combine the application of monosilicic acid into the soil with optimal doses of NPK. Our results are consistent with these studies in that the amount of basal fertilizers applied for each crop was sufficient to obtain a positive crop response from the combined application of silicon fertilizers and NPK.

A similar close correlation between the amount of SiO_2 and the yield of soybean ($P <0.01$, $R = 0.81$) in our field experiment indicates that the mechanism of the positive action of silicon may be similar. Other researchers also point to the agronomic efficiency of using silicon fertilizers for growing soybean under various soil and climatic conditions. For instance, an increase in soybean yield by 7.5–13.6% compared to control under silicon fertilizer was determined in China (Liang et al., 2015) and by 21% in Poland (Ciecierski, 2016). Consequently, the inclusion of silicon in the system of fertilization of agricultural crops in Ukraine can be considered a fairly reasonable step, although this does not exclude the need for a deeper study of the mechanisms of action of Si in various forms of silicon fertilizers and methods of their application.



(A)



(B)

Figure 2. The efficiency of the application of silicon fertilizers for corn (A) and soybean (B).

Conclusion

The growth-stimulating effect of potassium silicate on the indicators (germination capacity, germination energy, and germination synchronization index) of barley and corn seeds was found; the optimal concentration of the SiO_2 solution for pre-sowing seed treatment was 0.75%. The application of potassium silicate during sowing into the soil contributed to an increase in the aboveground mass and grain yield of spring barley, biomass yield of silage corn and soybean grain. The highest effect of 1 kg SiO_2 for these crops was determined at application rates of 105 kg SiO_2 ha^{-1}, 92 kg SiO_2ha^{-1} and 76 kg SiO_2ha^{-1}, respectively. The positive effect of foliar applications of silicon fertilizer was achieved only for soybean plants. The combined soil and foliar application of 60 kg SiO_2 ha^{-1} and 30 kg SiO_2 ha^{-1}, respectively, gave the maximum yield increase. The response of crops to the incorporation of potassium silicate into the soil expressed as yield increase compared to the control was in the following order: spring barley < silage corn < soybean. Based on the shown effectiveness of the use of silicon fertilizers under various soil and climatic conditions in other countries, further research is needed to establish the mechanisms of action of Si in various forms of silicon fertilizers and the methods of their application on chernozem soils in Ukraine.

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KORISNI UTICAJI SILICIJUMSKOG ĐUBRIVA NA POKAZATELJE KLIJANJA SEMENA, PRINOSA ZRNA JEČMA I SOJE I BIOMASE SILAŽNOG KUKURUZA

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R e z i m e

Cilj rada bio je da se utvrde optimalne doze i načini primene silicijumskog đubriva kod ječma, silažnog kukuruza i soje u klimatskim uslovima Ukrajine. Izvršen je niz laboratorijskih i poljskih ogleda, kao i statistička i analitička obrada podataka. Poljski ogled malih parcela je izveden na zemljištu tipa podzolasti černozem u NNC „Institut za pedološka i agrohemijska istraživanja po imenu O.N. Sokolovski" (Harkovska oblast, šumo-stepe Ukrajine). Laboratorijski ogledi su postavljeni u Petrijevim posudama korišćenjem različitih koncentracija kalijum silikata (0%, 0,5%, 0,75% i 1,0%) za procenu pokazatelja klijanja semena ječma i kukuruza. Pokazano je značajno stimulativno dejstvo kalijum silikata na klijanje i energiju klijanja semena ječma i kukuruza i utvrđena optimalna koncentracija rastvora za predsetveno tretiranje semena. Utvrđena je visoka pozitivna korelacija između količine primene SiO_2 i prinosa proučavanih useva ($P<0,01$; $R=0,7479$-$0,8682$). Utvrđeni su optimalni nivoi predsetvenog unošenja SiO_2 u zemljište za postizanje maksimalnih prinosa na zemljištu tipa podzolasti černozem (105 kg SiO_2 ha^{-1} za ječam, 92 kg SiO_2 ha^{-1} za silažni kukuruz i 76 kg SiO_2 ha^{-1} za soju). Takođe, za svaki od proučavanih useva utvrđeni su optimalni načini primene silicijumskih đubriva, koji će poboljšati njihovu produktivnost na zemljištima tipa černozem.

Ključne reči: silicijum, ishrana biljaka, produktivnost useva, mineralno đubrivo.

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