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A NANOSILICON PREPARATION IS SUPERIOR TO A BIOLOGICAL PREPARATION AND A CHEMICAL PREPARATION IN ACTIVITY TOWARDS PHOTOSYNTHETIC PRODUCTIVITY AND YIELD PARAMETERS OF SPRING WHEAT

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Abstract

Wheat is widely used as a food, technical and feed crop. Increased wheat yields can be achieved by mitigating biotic and abiotic stresses using a variety of technologies that include trace elements and growth regulators. Nanosilicon microfertilizer (NanoSilicon LLC, Russia) is an environmentally friendly product containing 50 % of pure colloidal-sized crystalline silicon. This work, for the first time, confirms the positive effect of the Nanosilicon preparation on photosynthetic potential and the net productivity of photosynthesis, the synthesis of chlorophyll, carotenoids and sugars and shows an advantage of Nanosilicon over the pesticide Vincite and an experimental biological product. Under the influence of Nanosilicon, the component structure of the spring wheat yield changed, namely, the number of productive stems, ears and 1000-grain weight increased. Our goal was to examine the effect of Nanosilicon preparation on spring wheat photosynthetic productivity and yield components in the conditions of the Orel region and to compare the effect of Nanosilicon with that of a chemical pesticide and a bioactive preparation. The experiment design included four treatments of spring wheat (*Triticum aestivum* L.) cv. Darya seeds (Federal Research Center for Grain-Legumes and Cereals, Streletskoe village, Oryol region, 2016-2019). The seeds were soaked for 2 hours before sowing in water, in chemical pesticide Vinzit (two controls), in a novel biological product based on buckwheat bioflavonoids, and in Nanosilicon concentrate (tests). During vegetation, the control and test treatments were twice applied to the growing plants at tillering and at stem extension phases. The energy of seed germination and germination rate were determined, the development of seed infections was assessed. The phenological phases (three leaves, tillering, stem extension, earing, flowering, milk ripeness, and full ripeness of the grain) were recorded. Photosynthetic potential (PP), photosynthetic productivity and net photosynthetic productivity (NPP) were evaluated, leaf area and the pigment content were measured. It was found that pre-sowing treatment of spring wheat seeds with Nanosilicon contributed to an 18.5 % increase in germination energy and a 5.5 % increase in germination rate as compared to the control treatments. Due to the Nanosilicon application, the plants were taller, resulting in more leaves until the end of the growing season, which indicates a longer leaf life compared to controls. The leaf area was 20.0 % larger at the earing-flowering period compared to the control (water), that was, 14.6 % larger for the biopreparation and 8.3 % larger for the pesticide Vincit. Photosynthetic capacity for control (water), Vincit, Nanosilicon, and the biopreparation was 633360, 686022, 1560384, and 1104894 $m^2 \cdot$ day/ha, respectively. NPP value for Nanosilicon was greater as compared to the controls, by 60-80 % for water and by 22.2 % for Vincit. The amounts of chlorophylls and carotenoids in plants were the greatest at the earing—flowering phase. Under the influence of Nanosilicon and the biological preparation, the synthesis of pigments increased by 20-30 % compared to the controls. Nanosilicon contributed to an increase in the synthesis of sugars in the process of photosynthesis to a lesser extent than the biological product, which can be explained by the difference in the distribution of assimilates and a large accumulation of proteins. The advantages of the Nanosilicon over the bioactive preparation in the number of grains and the 1000-seed weight were minor. Under the effect of Nanosilicon, the number of productive stems increased by 33.7 %, the number of ears by 38.7 %, the ear weight by 26.8 %, the number of grains per ear by 19.2 grains, and the 1000-grain weight by 19.7 % as compared to the control. These indicators for the bioactive preparation were slightly lower than for Nanosilicon, but higher than in control treatments. For four years, the grain yield under the influence of Vincite was approximately 8 % higher compared to the control (water) and from 9 to 16.6 % higher due to Nanosilicon and the bioactive preparation.

Keywords: spring wheat, Nanosilicon, biological product, germination energy, germination rate, net photosynthetic productivity, yield components

Wheat, a food, industrial and fodder crop is grown on 30.3% of the grain sown area [1-4] in a wide range of climatic conditions and soils [5-7]. However, Trnka et al. [8] reported about various adverse weather events that can significantly affect wheat productivity in Europe. Climate change will lead to a reduction in the production of major cereals, with the exception of millet [9]. Technologies that mitigate the effects of biotic and abiotic stresses should increase wheat yields.

In recent decades, researchers and commercial farmers have paid significant attention to plant biostimulants and trace elements, in particular silicon. Silicon weakens the negative effects of abiotic stresses (metal toxicity, salinity, water stress, and temperature) and can reduce biotic stress [10-12]. The use of silicon fertilizers significantly increases plant resistance to diseases and pests. Silicon activates protective mechanisms, e.g., the synthesis of phytoalexins, antioxidant defense enzymes, and jasmonic acid signaling [13-15]. Silicon fertilizers have positive effects on various soils when growing rice, sugarcane, barley, sorghum, maize, wheat, oats, rye, sunflowers, beans, broad beans, soybeans, clover, alfalfa, millet, tomatoes, cucumbers, tobacco, sugar beets, lemons, tangerines, grapes, apples, and melons [16-18]. Under the influence of silicon, the intensity and productivity of photosynthesis increases. Meanwhile, the contribution of the traits that determine the production process in plants, which is carried out due to the functioning of the photosynthesizing system, is still not clear [19].

Additional photosynthesis can occur due to an increase in its daily duration or in leaf area. In grain crop, an increase in the potential number of grains and their size results from an increase in photosynthesis [6, 20, 21].

Nanosilicon microfertilizer (NanoKremniy LLC, Russia), a promising plant stimulant for grain crops, is an environmentally friendly product containing 50% pure colloidal crystalline silicon. Polyethylene glycol (food additive E1521), 6% iron, 1% copper, 0.5% zinc, 20% humic acids, 8% fulvic acids, 0.02% calcium, 0.01% boron serve as stabilizers. Unlike ordinary silicon, Nanosilicon which consists of active silicon particles of 5 nm or larger without impurities, can be completely assimilated by plants [22]. Studies conducted on spring wheat [22-24], winter wheat [25] and winter barley [26] showed that Nanosilicon contributed to an increase in the grain number per ear and a 34-35% increase in yield upon seed treatment and double spraying plants.

Recent years have witnessed growing interest in regulation and modification of physiological processes in plants, including optimized use of sunlight throughout the growing cycle. Though the dry matter production is a result of photosynthesis, it is very difficult to find a relationship between this process and the yield size. An increase in the efficiency of photosynthesis and crop yields is due primarily to the genetic improvement but also to proper variety-specific growing and farming technology and plant stimulants.

This work is the first to show the positive effect of the Nanosilicon on the photosynthetic potential, net productivity of photosynthesis, the synthesis of chlorophyll, carotenoids, sugars and the advantage of this preparation over the pesticide Vincit, KS, and a biological stimulant. Under the influence of Nanosilicon, the structure of the spring wheat crop changed, namely, the number of productive stems, ears and the 1000-grain weight increased.

Our goal was to study the effect of the Nanosilicon on the photosynthetic productivity and structure of the spring wheat yield in the Orel region and to compare the action of Nanosilicon with a chemical pesticide and an experimental bioactive preparation.

Materials and methods. Field experiments were carried out on spring wheat (*Triticum aestivum* L.) variety Daria of the (Federal Research Center of Legumes and Groats, Streletskoye village, Orel Province, 2016-2019). The variety is included in the State Register of Breeding Achievements approved for use in the Central and Central Black Earth Regions (2016). The climate of the territory is moderately continental with a sufficient amount of heat and moisture, but precipitations are unevenly distributed. The soils of the experimental site are dark gray forest, medium loamy. In controls and treatments, 7 m^2 plots were used in four replicates. Seeds were soaked for 2 hours before sowing. During the growing season, vegetative plants were twice sprayed (at tillering and stem extension phases).

In two controls, the seeds were soaked in water (10 l/t) or in the Vincit, KS (Cheminova A/S, France, 1.5 l/t) with the use of 10 l/t working solution. For an experimental biological (Orel State Agrarian University, Russia), the dosages were 1.56 ml/t (working solution 10 l/t) for seed soaking and 3.12 ml/ha (working solution 200 l/ha) for plant spraying. For Nanosilicon (LLC NanoKremniy, Russia), the dosages were 150 g/t (working solution 10 l/t) for seed soaking and 50 g/ha (working solution 200 l/ha) for plant spraying [27].

Germination energy (percentage of seeds germinated on day 3) and seed germination rate (percentage of seeds germinated on day 7) were determined according to GOST 12038-84 “Seeds of agricultural crops. Methods for determining germination” (Mocow, 2004). Seed infections was assessed according to GOST 12044-93 “Seeds of agricultural crops. Methods for determining the incidence of diseases” (Mocow, 2011). Seed contamination was determined on day 10 in germinators. The total infection percentage was expressed compered to 100% infection.

Phenological observations covered the development stages of 2-3 leaves, tillering, stem extension, heading, flowering, milk ripeness, and full grain ripeness. The net productivity of photosynthesis was determined according to Nichiporovich [28] and calculated based on the increase in dry biomass over the test period per the average leaf area [29]. The leaf area was measured according to Moiseev et al. [29]. For examination, 10 plants were taken for each control and treatment.

The content of pigments in plants was determined according to V.F. Gavrilenko et al. [30] after homogenizing the leaves in a porcelain mortar and extracting with 100% acetone. The concentration of pigments in the extracts was measured by absorption at λ = 662 nm (chlorophyll a), λ = 644 nm (chlorophyll b) and λ = 440.5 nm (carotenoids) (an automated single-beam spectrophotometer SF-56, Lomo- Spectrum, Russia).

The tables and figures show the arithmetic means (*M*) and standard errors of the means (±SEM). The significance of the differences was determined by the Student’s *t*-test at P = 0.95. For data processing, we used the methodological recommendations of B.A. Dospekhova [31]. The paper presents data on photosynthesis obtained in 2019, and data on yield under the influence of Nanosilicon and an experimental biological product for all four years of the study.

Results. In 2019, the phases of development of spring wheat fell on the following dates: stage of the 2nd leaf (shoots) on May 6, tillering on May 20, tillering—the beginning of stemming on May 31, heading—the beginning of flowering on June 13, end of flowering on June 23, and beginning of ripening on July 5.

The minimum seed infection (0.8%) occurred with the use of the agrochemical disinfectant Vincite, KS. In the control without treatment, the infection varied over years within 8.3-12.6%, when treated with Nanosilicon within 7.8-9.2%, and with an experimental biological within 6.4-9.5%.

In lab tests with pre-sowing seed treatment, the maximum increase in germination energy by 18.5% and germination rate by 5.5% ($p < 0.05$) compared to control occurred upon application of Nanosilicon and the experimental biological. In the field trials, this difference was about 10%. Apparently, the increase in seed germination rate under the influence of silicon was due to the stimulation of root growth. Growth regulators, penetrating plant cells, change the activity of physiological processes, primarily the synthesis of hormones and enzymes, promoting cell division, root growth, and activation of aquaporin genes [32-34].

Photosynthetic productivity depends on physiological and biochemical processes that determine the size and quality of the yield, but there is still no clear understanding of how these processes are regulated and may be controlled [35, 36]. Heyneke et al. [37] emphasize the important role of metabolic pathways not directly involved in photosynthesis. The pathways that attract main attention are those ensuring a better carbon assimilation, an increase in the efficiency of photosynthesis and, as a result, the higher yield of biomass [38]. For example, ribulose 1,5-bisphosphate carboxylase/oxygenase (RuBisCo), a fundamental carbon fixation enzyme, is extremely ineffective, and many strategies to improve the photosynthetic capacity of plants are focused on overcoming the limitations of the enzyme by improving its activity and regulation [39].

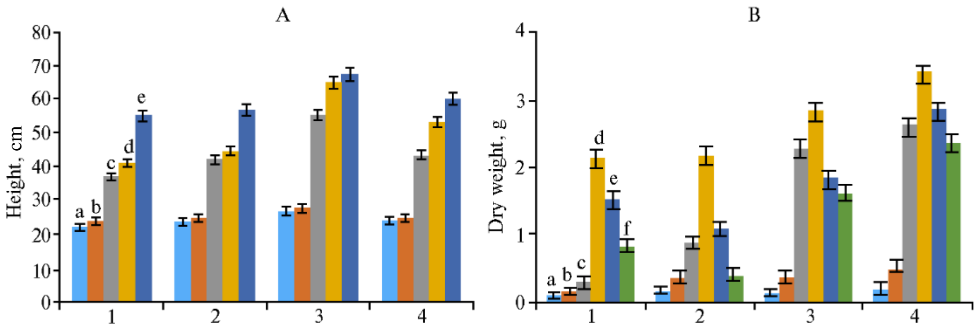

Fig. 1. Heigh (A) **and dry weigh** (B) **of spring wheat (*Triticum aestivum* L., cv. Daria) plants at 2nd leaf (seedings)** (a)**, tillering** (b)**, tillering—beginning of stem extension** (c)**, tillering—beginning of heading** (d)**, end of heading** (e)**, and beginning of ripening** (f) **stages as influenced by various treatments:** 1 — water, 2 — Vincite, KS desingectant, 3 — Nanosilicon, 4 — an experimental biological ($n = 10$, $M\pm$SEM; Streletskoe settlement, Orel Province, 2019).

Starting with wheat seedlings, there was an advantage in plant development due to Nanosilicon application as compared to the controls (Fig. 1). Plants from seeds treated with an experimental biological lagged somewhat behind, but were significantly more powerful than the control plants and exceeded them in dry weight. The use of Nanosilicon and biological product provided the greatest and significant excess compared to control (by 27-34%, $p < 0.05$).

The total leaf area during the beginning of the tillering—beginning of heading stages was 15834.00 m^2 for the control (water), reaching 17150.55, 19009.60, and 18141.10 m^2 for Vincite, KS, Nanosilicon, and the experimental biological, respectively. Spring wheat reached the largest leaf areas with Nanosilicon and the biological, exceeding the control (water) by 20.0 and 14.6%.

According to Mokronosov [40] and Nikitin [41], in plants that have more leaves, proper agrotechnologies and a shorter growing season can provide greater productivity even with a low intensity of photosynthesis. However, in our opinion, with an increase in the assimilating leaf area, it is worth to consider the total amount of chlorophylls, and hence the nutritional value of the crop. Meanwhile, the increase in leaf area per hectare for the entire growing season (the photosynthetic potential PP), is an indicator of the duration of the photosynthetic activity.

The sowings with PP of 2 million $m^2 \cdot$ day/ha are recognized optimal [42, 43].

With Nanosilicon and the experimental biological, the PP of spring wheat crops increased during the growing season due to an increase in the leaf area. In control (water) and upon treatments with Vincite, KS, Nanosilicon, and the biological, the PP values were 633360, 686022, 1560384, and 1104894 $m^2 \cdot$ day/ha, respectively.

The leaf area correlates with plant biomass which was the largest with Nanosilicon and the biological (see Fig. 1).

The use of growth regulators and biologicals affects the crop production process, induces plant immunity and allows people to have environmentally friendly food [44]. Pre-sowing treatment with growth regulators has a positive effect on the yield and baking properties of the products, including the protein and starch content, the amount and quality of gluten, and the bulk density of grain [45]. In corn subjected to salt stress and cold shock, application of salicylic acid, mannitol, and thiourea regulates plant growth and responses to oxidative stress, increases growth rate, leaf surface index, plant height, grain yield, and total dry matter accumulation [46, 47].

The final yield depends on other factors, among which the variety, soil and climatic conditions play a fundamental role. The formation of productivity is determined by the net productivity of photosynthesis (NPP) which depends on the assimilation surface of plants [48]. To increase the yield potential, it is necessary to increase the total biomass, but if sunlight during the growing season is already fully used, then an increase in biomass requires photosynthesis occurred in a more efficient way [48, 49]. The concept of more efficient photosynthesis to increase yields has been considered by many researchers. Long et al. [50] identified the goals as improving the kinetic properties of RuBisCo, modifying C3 crops to confer the ability of C4 photosynthesis, and improving the canopy architecture. The classical approach is the change in stomatal conductance [51, 52].

In our studies, the NPP value directly depended on the treatment (Table 1). With Nanosilicon and the biological, the NPP was higher compared to both controls. Apparently, in the plants treated with these preparations, the contribution of assimilating organs was greater and the consumption of carbohydrates for respiration was less. Depending on the treatments, the value of NPP in spring wheat varied from 6.86±0.28 at the beginning of stem extension to 18.30±0.80 $g/m^2 \cdot$ day by the end of heading.

1. Net productivity of photosynthesis ($g/m^2 \cdot$ day) **in spring wheat (*Triticum aestivum* L., cv. Daria) plants depending on treatments and the stages of plant development** (n = 10, M±SEM; Streletskoe settlement, Orel Province, 2019 год)

Treatment	Stage				
	tillering	tillering—beginning of stem extension	tillering — beginning of heading	end of heading	beginning of ripening
Control (water)	0.49±0.02	6.86±0.28	7.70±0.35	10.10±0.37	5.00±0.24
Control (Vincite, KS)	1.39±0.06	7.90±0.34	8.80±0.28	9.50±0.33	6.11±0.45
Nanosilicon	1.40±0.07	8.70±0.41	14.20±0.55	18.30±0.80	10.33±0.80
Experimental biological	2.29±0.10	8.20±0.41	12.20±0.40	16.90±0.74	9.30±0.43

N o t e. For description of the treatments, see *Materials and methods*. The observed values for the Student's t-test exceed the tabulated values at df = 9 and P = 0.95, which indicates the reliability of the obtained differences in the net productivity of photosynthesis compared to the control values.

As is known, an increased leaf area in crops can reduce photosynthetic productivity, but this did not happen in our studies. The maximum leaf area at heading was 18000 m^2/ha which is far from optimal values [53].

The work of pigments that play a key role in photosynthesis depends on climatic and ecological factors [54, 55]. According to Andrianova et al. [35], the amount of chlorophyll during tillering and stem extension may indicate the potential productivity of plants, since the formation of a high yield depends on the size of the assimilation apparatus and the time of its functioning.

In our experiments, the synthesis of pigments also reflected the effect of Nanosilicon on photosynthesis. The amount of pigments in leaves increased over the growing season by 20-70%, depending on the time of leaf functioning (Fig. 2, A). The amounts of chlorophyll and carotenoids were the greatest on July 13, that is, at the tillering—heading stage.

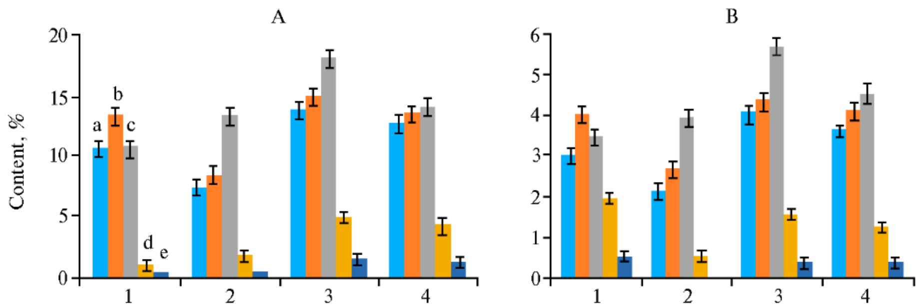

Fig. 2. Accumulation of chlorophylls a and b (A) **and carotenoids** (Б) **in spring wheat (*Triticum aestivum* L., cv. Daria) plants at tillering** (a)**, tillering—beginning of stem extension** (b)**, tillering—beginning of heading** (c)**, end of heading** (d)**, and beginning of ripening** (e) **stages as influenced by various treatments:** 1 — water, 2 — Vincite, KS desingectant, 3 — Nanosilicon, 4 — an experimental biological (n = 10, M±SEM; Streletskoe settlement, Orel Province, 2019).

In all experimental periods, plants treated with Nanosilicon and the biological exceeded the control in chlorophyll contents by 20-30%. Note, even during grain maturation, the leaves of these plants remained green which indicates a longer photosynthetic activity.

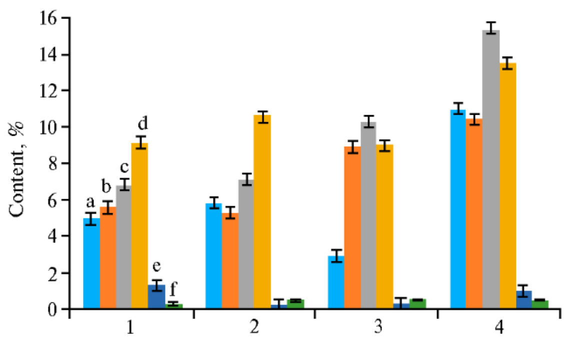

Fig. 3. Accumulation of sugars in spring wheat (*Triticum aestivum* L., cv. Daria) plants at plants at 2nd leaf (seedings) (a)**, tillering** (b)**, tillering—beginning of stem extension** (c)**, tillering—beginning of heading** (d)**, end of heading** (e)**, and beginning of ripening** (f) **stages as influenced by various treatments:** 1 — water, 2 — Vincite, KS desingectant, 3 — Nanosilicon, 4 — an experimental biological (n = 10, M±SEM; Streletskoe settlement, Orel Province, 2019).

Carotenoids absorb light in the blue-green region of the solar spectrum and transfer energy to chlorophylls, thereby expanding the wavelength range of light that can drive photosynthesis. They serve to increase the overall efficiency of photosynthetic light reactions and protect photosynthesizing organisms from overexposure to light [56]. The content of carotenoids often positively correlates with the amount of chlorophyll [57]. Our data confirm this conclusion (see Fig. 2, B). It is widely known that silicon significantly stimulates the growth of many plant species via increasing photosynthetic activity, leaf area, and chlorophyll content [58-62].

Nanosilicon enhanced sugar production to a lesser extent than the experimental biological, which can be explained by the redistribution of assimilates and, probably, a large accumulation of proteins in spring wheat under the influence of Nanosilicon (Fig. 3). Our hypothesis is in line with the data showing that mineral fertilizers significantly increase the mass fraction of protein and gluten in the grain of spring wheat [63-65]. According to the report of Lavoy et al. [66], an increase in the protein content in wheat seeds under the influence of mineral fertilizers is due to a high correlation between the grain protein content and nitrate reductase activity, as is confirmed by Tao et al. [67]. The elevated grain sugar levels we observed under the influence of the experimental biological may have been associated with the level of salicylic acid which has a positive effect on the assimilation activity of plants [68, 69].

According to Mokronosov [70], growth regulators and phytohormones which contribute to a change in the outflow of assimilates from leaves to reproductive organs can ensure the greatest economic yield. Growth regulators and stimulants help to increase plant immunity, increase yields, and improve quality for obtaining environmentally friendly food [53].

We have found that the Nanosilicon application is an effective and low-cost technique to increase the overall yield of spring wheat. At the end of the growing season, the collected sheaves were heavier than in the controls and superior in the ear size. Under the influence of Nanosilicon, the number of productive stems increased by 33.7, of ears by 38.7, the weight of an ear by 26.8, the number of grains per ear by 19.2, and the 1000-grain weight by 19.7% compared to the control (water) (Table 2). For the biological, the indicators were slightly lower than for Nanosilicon but higher compared to both controls.

2. Yield components in spring wheat (*Triticum aestivum* L., cv. Daria) depending on treatments (*n* = 10, *M*±SEM; Streletskoe settlement, Orel Province, 2019 год)

Treatment	Productive stem number per 1 m^2	Ear		Grain number per ear	1000-grain weight, g	Ear number
		length, cm	weight, g			
Control (water)	326±11.2	8.2±0.37	1.9±0.08	32.8±0.84	37.7±1.49	300±11.6
Control (Vincite, KS)	276±10.2	8.3±0.31	1.9±0.08	33.1±1.47	40.1±1.94	244±10.6
Nanosilicon	436±17.3	9.0±0.43	2.4±0.11	39.6±1.63	45.1±2.00	416±16.9
Experimental biological	344±11.5	8.9±0.42	2.3±0.11	41.2±1.41	44.8±1.64	319±12.7

N o t e. For description of the treatments, see *Materials and methods.* The observed values for the Student's *t*-test exceed the tabulated values at df = 9 and P = 0.95, which indicates the reliability of the obtained differences compared to the control values.

3. Four-year yields of spring wheat (*Triticum aestivum* L., cv. Daria) depending on treatments (*n* = 10, *M*±SEM; Streletskoe settlement, Orel Province)

Treatment	Yield, c/hara				Gain to the control (water), %			
	2016	2017	2018	2019	2016	2017	2018	2019
Control (water)	28.9±1.38	38.2±1.61	41.3±2.04	45.1±2.00				
Control (Vincite, KS)	31.4±1.20	41.4±0.91	44.5±2.11	47.3±2.01	8.65	8.40	7.80	4.88
Nanosilicon	33.7±1.45	43.7±2.03	45.1±2.19	49.4±1.91	16.61	14.40	9.20	9.53
Experimental biological	34.5±1.55	43.9±2.07	45.3±1.71	48.9±2.16	19.01	14.90	9.20	8.43
LSD_{05}	1.2	1.4	1.2	0.9				

N o t e. For description of the treatments, see *Materials and methods.* The observed values for the Student's *t*-test exceed the tabulated values at df = 9 and P = 0.95, which indicates the reliability of the obtained differences compared to the control values.

Wheat yield under the influence of Nanosilicon increased due to an increase in both the grain number per ear and grain weight (Table 3). When treated with Vincite, KS, the yield increased by 8% compared to the control (water), with the exception of 2019 (only by 5%), and under the influence of Nanosilicon and the biological, its increase was 9-19%.

Thus, the Nanosilicon turned out to be more effective towards the spring wheat cv. Daria than the agrochemical Vincite, KS but differed little from the experimental biological product based on buckwheat bioflavonoids. Seed pre-treatment with Nanosilicon and the biological increased the germination energy by 18.5% and germination rate by 5.5% ($p < 0.05$) compared to the controls (water and Vincite, KS). The height of plants, the number and area of leaves, the photosynthetic potential, the indices of net productivity of photosynthesis (NPP), and the amounts of chlorophylls and carotenoid indicate superiority of Nanosilicon over the controls. The NPP indices for Nanosilicon were 60-80% higher than the control (water) and 22.2% higher compared to agrochemical Vincite, KS. Under the influence of Nanosilicon and the biological, the synthesis of pigments increased by 20-30%. The biological product largely influences the synthesis of sugars than Nanosilicon, which can be explained by the difference in the redistribution of assimilates and the enhanced accumulation of proteins in plants under the influence of silicon. Nanosilicon provides an increase in the grain number per ear and the 1000-grain weight compared to both controls. The advantage over the bioactive proparation was insignificant. Nanosilicon increased the number of productive stems by 33.7, of ears by 38.7, the weight of an ear by 26.8, the grain number per ear by 19.2, and the 1000-grain weight by 19.7% compared to control ($p < 0.05$). Indicators for the biological product were slightly lower than for Nanosilicon but higher than the control. Wheat yield for four years under the influence of Nanosilicon and the biological increased by 9.0-16.6% as compared to control.

REFERENCES

1. *Food and Agriculture Organization Corporate Statistical Database*. Available: http://www.fao.org/faostat/ru/#data/QC. No date.
2. Khoury S.K., Bjorkman A.D., Dempewolf H., Ramirez-Villegas J., Guarino L., Jarvis A., Rieseberg L.H., Struik P.C. Increasing homogeneity in global food supplies and the implications for food security. *Proceedings of the National Academy of Sciences,* 2014, 111(11): 4001-4006 (doi: 10.1073/pnas.1313490111).
3. Johnson V.A., Briggle L.W., Axtel J.D., Bauman L.F., Leng E.R., Johnston T.H. Grain crops. In: *Protein resources and technology*. M. Milner, N.S. Scrimshaw, D.I.C. Wang (eds.). AVI Publishin, Westport, CT, USA, 1978: 239-255.
4. Giraldo P., Benavente E., Manzano-Agugliaro F., Gimenez E. Worldwide research trends on wheat and barley: a bibliometric comparative analysis. *Agronomy*, 2019, 9(7): 352 (doi: 10.3390/agronomy9070352).
5. Singh R.P., Singh P.K., Rutkoski J., Hodson D.P., He X., Jorgensen L.N., Hovmøller M.S., Huerta-Espino J. Disease impact on wheat yield potential and prospects of genetic control. *Annual Review of Phytopathology*, 2016, 54: 303-322 (doi: 10.1146/annurev-phyto-080615-095835).
6. Hawkesford M.J., Araus J.-L., Park R., Calderini D., Miralles D., Shen T., Zhang J., Parry M.A.J. Prospects of doubling global wheat yields. *Food and Energy Security*, 2013, 2(1): 34-48 (doi: 10.1002/fes3.15).
7. Slafer G.A., Savin R., Sadras V.O. Coarse and fine regulation of wheat yield components in response to genotype and environment. *Field Crops Research*, 2014, 157: 71-83 (doi: 10.1016/j.fcr.2013.12.004).
8. Trnka M., Rötter R.P., Ruiz-Ramos M., Kersebaum K.C., Olesen J.E., Žalud Z., Semenov M.A. Adverse weather conditions for European wheat production will become more frequent with climate change. *Nature Climate Change*, 2014, 4(7): 637-643 (doi: 10.1038/NCLIMATE2242).
9. Wang J., Vanga S.K., Saxena R., Orsat V., Raghavan V. Effect of climate change on the yield of cereal crops: a review. *Climate,* 2018, 6(2): 41 (doi: 10.3390/cli6020041).
10. Yavaş İ., Ünay A. The role of silicon under biotic and abiotic stress conditions. *Türkiye Tarımsal Araştırmalar Dergisi*, 2017, 4(2): 204-209 (doi: 10.19159/tutad.300023).
11. Cooke J., Leishman M.R. Consistent alleviation of abiotic stress with silicon addition: a meta-analysis. *Functional Ecology*, 2016, 30(8): 1340-1357 (doi: 10.1111/1365-2435.12713).
12. Mir R.A., Bhat K.A., Shah A.A., Zargar S.M. Role of silicon in abiotic stress tolerance of plants. In: *Improving abiotic stress tolerance in plants*. CRC Press, 2020 (doi: 10.1201/9780429027505-15).
13. Frew A., Weston L.A., Reynolds O.L., Gurr G.M. The role of silicon in plant biology: a paradigm shift in research approach. *Annals of Botany*, 2018, 121(7): 1265-1273 (doi: 10.1093/aob/mcy009).
14. Abdel-Haliem M.E.F., Hegazy H.S., Hassan N.S., Naguib D.M. Effect of silica ions and nano silica on rice plants under salinity stress. *Ecological Engineering,* 2017, 99: 282-289 (doi: 10.1016/j.ecoleng.2016.11.060).
15. Luyckx M., Hausman J.-F., Lutts S., Guerriero G. Silicon and plants: current knowledge and technological perspectives. *Front. Plant Sci.*, 2017, 8: 411 (doi: 10.3389/fpls.2017.00411).
16. Liang Y., Nikolic M., Bélanger R., Gong H., Song A. Silicon uptake and transport in plants:

physiological and molecular aspects. In: *Silicon in agriculture*. Y. Liang, M. Nicolic, R. Bélanger, H. Gong, A. Song (eds). Springer, Dordrecht, 2015: 69-82 (doi: 10.1007/978-94-017-9978-2).

17. Kozlov A.V., Kulikova A.Kh., Yashin E.A. *Vestnik Mininskogo universiteta*, 2015, 2: 23-31 (in Russ.).
18. Al-Aghabary K., Zhu Z., Shi Q. Influence of silicon supply on chlorophyll content, chlorophyll fluorescence and anti-oxidative enzyme activities in tomato plants under salt stress. *Journal of Plant Nutrition*, 2005, 27(12): 2101-2115 (doi: 10.1081/PLN-200034641).
19. Molero G., Joynson R., Pinera-Chavez F.J., Gardiner L., Rivera-Amado C., Hall A., Reynolds M.P. Elucidating the genetic basis of biomass accumulation and radiation use efficiency in spring wheat and its role in yield potential. *Plant Biotechnology Journal,* 2019, 17(7): 1276-1288 (doi: 10.1111/pbi.13052).
20. Richards R.A. Selectable traits to increase crop photosynthesis and yield of grain crops. *Journal of Experimental Botany*, 2000, 51(Suppl. 1): 447-458 (doi: 10.1093/jexbot/51.suppl_1.447).
21. Curtis T., Halford N.G. Food security: the challenge of increasing wheat yield and the importance of not compromising food safety. *Annals of Applied Biology*, 2014, 164(3): 354-372 (doi: 10.1111/aab.12108).
22. Kosachev I.A., Chernyshkov V.N. *Vestnik Altaiskogo gosudarstvennogo agrarnogo universiteta*, 2018, 9(167): 23-28 (in Russ.).
23. Semina S.A., Ostroborodova N.I. *Materialy Mezhdunarodnoi nauchno-prakticheskoi konferentsii, posvyashchennoi 80-letiyu d.s.-kh.n., prof. Sozyrko Kh.D. «Aktual'nye voprosy primeneniya udobrenii v sel'skom khozyaistve»* [Proc. Int. Conf. «Topical issues of the use of fertilizers in agriculture»]. Vladikavkaz, 2017: 63-65 (in Russ.).
24. Serkova O.P., Zhandarova S.V. *Materialy XIV Mezhdunarodnoi nauchno-prakticheskoi konferentsii «Agrarnaya nauka — sel'skomu khozyaistvu»* [Proc. Int. Conf. «Agricultural science for agriculture prcatice»]. Barnaul, 2019, kn. 2: 246-247 (in Russ.).
25. Mnatsakanyan A.A., Chuvarleeva G.V. *Materialy Mezhdunarodnoi nauchno-prakticheskoi konferentsii molodykh uchenykh i spetsialistov «Fundamental'nye osnovy upravleniya selektsionnym protsessom sozdaniya novykh genotipov rastenii s vysokimi khozyaistvenno tsennymi priznakami produktivnosti, ustoichivosti k bio- i abiostressoram»* [Proc. Int. Conf. «Foundations for breeding new plant genotypes with high economically valuable traits of productivity, resistance to bio- and abiostressors»]. Orel, 2017: 135-139 (in Russ.).
26. Chuvarleeva G.V., Mnatsakanyan A.A. *Materialy nauchno-prakticheskoi konferentsii, posvyashchennoi 110-letiyu so dnya rozhdeniya akademika V.I. Shempelya* [Proc. Conf. dedicated to the 110th anniversary of the birth of Academician V.I. Shempel]. Zhodino, 2018: 114-116 (in Russ.).
27. Pavlovskaya N.E., Gor'kova I.V., Gagarina I.N., Borodin D.B., Borzenkova G.A. *Sredstvo dlya predposevnoi obrabotki semyan gorokha. RU 2463759 C1 MPK A01C 1/06, A01C 1/08. Federal'noe gosudarstvennoe obrazovatel'noe uchrezhdenie vysshego professional'nogo obrazovaniya "Orlovskii gosudarstvennyi agrarnyi universitet" (RF). № 2011117691/13. Zayavl. 03.05.2011. Opubl. 20.10.2012. Byul. № 29* [Means for pre-sowing treatment of pea seeds. RU 2463759 C1 MPK A01C 1/06, A01C 1/08. Federal State Educational Institution of Higher Professional Education "Oryol State Agrarian University" (RF). № 2011117691/13. Appl. 03.05.2011. Publ. 20.10.2012. Bull. № 1 №29] (in Russ.).
28. Nichiporovich A.A., Strogonova L.E., Chmora S.N., Vlasova M.P. *Fotosinteticheskaya deyatel'nost' rastenii v posevakh (Metody i zadachi ucheta v svyazi s formirovaniem urozhaev)* [Photosynthetic activity of plants in crops: methods and tasks with regard to crop formation)]. Moscow, 1961 (in Russ.).
29. Moiseev V.P., Reshetskii N.P. *Fiziologiya i biokhimiya rastenii: metodicheskie ukazaniya* [Plant physiology and biochemistry: guidelines]. Gorki, 2009 (in Russ.).
30. Gavrilenko V.F., Ladygina M.E., Khandobina L.M. *Bol'shoi praktikum po fiziologii rastenii* /Pod redaktsiei B.A. Rubina [Workshop on plant physiology. B.A. Rubin (ed.)]. Moscow, 1975 (in Russ.).
31. Dospekhov B.A. *Metodika polevogo opyta (s osnovami statisticheskoi obrabotki rezul'tatov issledovanii)* [Methods of field trials]. Moscow, 1985 (in Russ.).
32. Westfall C.S., Muehler A.M., Jez J.M. Enzyme action in the regulation of plant hormone responses. *Journal of Biological Chemistry*, 2013, 288(27): 19304-19311 (doi: 10.1074/jbc.R113.475160).
33. Zhang Y., Xu S., Ji F., Hu Y., Gu Z., Xu B. Plant cell wall hydrolysis process reveals structure—activity relationships. *Plant Methods*, 2020, 16: 147 (doi: 10.1186/s13007-020-00691-5).
34. Liu P., Yin L., Wang S., Zhang M., Deng X., Zhang S., Tanaka K. Enhanced root hydraulic conductance by aquaporin regulation accounts for silicon alleviated salt-induced osmotic stress in *Sorghum bicolor* L. *Environmental and Experimental Botany,* 2015, 111: 42-51 (doi: 10.1016/j.envexpbot.2014.10.006).
35. Andrianova Yu.E., Tarchevskii I.A. *Khlorofill i produktivnost' rastenii* [Chlorophyll and plant productivity]. Moscow, 2000 (in Russ.).
36. Ort D., Melandri B.A., Yunge V., Uitmarsh Dzh. *Fotosintez. Tom 2* /Pod redaktsiei D.R. Govindzhi [Photosynthesis. Volume 2]. Moscow, 1987 (in Russ.).

37. Heyneke E., Fernie A.R. Metabolic regulation of photosynthesis. *Biochem. Soc. Trans.,* 2018, 46(2): 321-328 (doi: 10.1042/BST20170296).
38. Timm S. The impact of photorespiration on plant primary metabolism through metabolic and redox regulation. *Biochem. Soc. Trans.*, 2020, 48(6): 2495-2504 (doi: 10.1042/BST20200055).
39. Andralojc P.J., Carmo-Silva E., Degen G.E., Parry M.A.J. Increasing metabolic potential: C-fixation. *Essays Biochem.,* 2018, 62(1): 109-118 (doi: 10.1042/EBC20170014).
40. Mokronosov A.T. V sbornike: *Fiziologiya rastenii na sluzhbe prodovol'stvennoi programmy SSSR* [In: Plant physiology for the USSR food program. Part 2]. Moscow, 1988, ch. 2: 3-18 (in Russ.).
41. Nikitin S.N. *Uspekhi sovremennogo estestvoznaniya*, 2017, 1: 33-38 (in Russ.).
42. Nichiporovich A.A. V sbornike: *Fotoregulyatsiya metabolizma i morfogeneza rastenii* [In: Photo-regulation of plant metabolism and morphogenesis]. Moscow, 1975: 228-244 (in Russ.).
43. Sinegovskaya V.T., Abrosimova T.E. *Vestnik Rossiiskoi akademii sel'skokhozyaistvennykh nauk*, 2006, 5: 43-45 (in Russ.).
44. Timoshenko E.V. *MNIZH Mezhdunarodnyi nauchno-issledovatel'skii zhurnal*, 2015, 41(10-3): 68-70 (doi: 10.18454/IRJ.2015.41.092) (in Russ.).
45. Isaychev V., Andreev N., Bogapova M. The influence of growth regulators on the productive capacity of spring wheat. *BIO Web Conf. Int. Scientific-Practical Conf. Agriculture and Food Security: Technology, Innovation, Markets, Human Resources.* Ulyanovsk, 2020, 17: 5 (doi: 10.1051/bioconf/20201700106).
46. Waqas M.A., Khan I., Akhter M.J., Noor M.A., Ashraf U. Exogenous application of plant growth regulators (PGRs) induces chilling tolerance in short-duration hybrid maize. *Environmental Science and Pollution Research,* 2017, 24: 11459-11471 (doi: 10.1007/s11356-017-8768-0).
47. Kaya C., Sonmez O., Aydemir S., Ashraf M., Dikilitas M. Exogenous application of mannitol and thiourea regulates plant growth and oxidative stress responses in salt-stressed maize (*Zea mays* L.). *Journal of Plant Interactions*, 2013, 8(3): 234-241 (doi: 10.1080/17429145.2012.725480).
48. Li X., Schmid B., Wang F., Paine C.E.T. Net assimilation rate determines the growth rates of 14 species of subtropical forest trees. *PLoS ONE*, 2016, 11(3): e0150644 (doi: 10.1371/journal.pone.0150644).
49. Evans J.R. Improving photosynthesis. *Plant Physiology*, 2013, 162(4): 1780-1793 (doi: 10.1104/pp.113.219006).
50. Long S.P., Zhu X.-G., Naidu S.L., Ort D.R. Can improvement in photosynthesis increase crop yields? *Plant, Cell & Environment*, 2006, 29(3): 315-330 (doi: 10.1111/j.1365-3040.2005.01493.x).
51. Condon A.G., Farquhar G.D., Richards R.A. Genotypic variation in carbon isotope discrimination and transpiration efficiency in wheat: leaf gas-exchange and whole plant studies. *Australian Journal of Plant Physiology,* 1990, 17(1): 9-22 (doi: 10.1071/PP9900009).
52. Rebetzke G.J., Rattey A.R., Farquhar G.D., Richards R.A., Condon A.G. Genomic regions for canopy temperature and their genetic association with stomatal conductance and grain yield in wheat. *Functional Plant Biology*, 2013, 40(1): 14-33 (doi: 10.1071/FP12184).
53. Nichiporovich A.A., Asrorov K.A. V knige: *Fotosintez i ispol'zovanie solnechnoi energii* [In: Photosynthesis and the use of solar energy]. Leningrad, 1971: 5-18 (in Russ.).
54. Myśliwa-Kurdziel B., Latowski D., Strzałka K. Chapter Three. Chlorophylls c — Occurrence, synthesis, properties, photosynthetic and evolutionary significance. *Advances in Botanical Research*, 2019, 90: 91-119 (doi: 10.1016/bs.abr.2019.04.002).
55. Golovko T.K., Tabalenkova G.N., Dymova O.V. *Botanicheskii zhurnal,* 2007, 92: 1732-1742 (in Russ.).
56. Hashimoto H., Uragami C., Cogdell R.J. Carotenoids and photosynthesis. In: *Carotenoids in nature. Subcellular biochemistry, vol. 79.* C. Stange (eds.). Springer, Cham, 2016: 111-139 (doi: 10.1007/978-3-319-39126-7_4).
57. Ivanov L.A., Ivanova L.A., Ronzhina D.A., Yudina P.K. *Fiziologiya rastenii*, 2013, 60(6): 856-864 (doi: 10.7868/S0015330313050072) (in Russ.).
58. Bae E.J., Lee K.S., Huh M.R., Lim C.S. Silicon significantly alleviates the growth inhibitory effects of NaCl in salt-sensitive «Perfection» and «Midnight» Kentucky bluegrass (*Poa pratensis* L). *Hortic. Environ. Biotechnol.*, 2012, 53: 477-483 (doi: 10.1007/s13580-012-0094-3).
59. Lee S.K., Sohn E.Y., Hamayun M., Yoon J.Y., Lee I.J. Effect of silicon on growth and salinity stress of soybean plant grown under hydroponic system. *Agroforest Syst.*, 2010, 80: 333-340 (doi: 10.1007/s10457-010-9299-6).
60. Al-Aghabary K., Zhu Z., Shi Q. Influence of silicon supply on chlorophyll content, chlorophyll fluorescence and anti-oxidative enzyme activities in tomato plants under salt stress. *Journal of Plant Nutrition*, 2005, 27(12): 2101-2115 (doi: 10.1081/PLN-200034641).
61. Romero-Aranda M.R., Jurado O., Cuartero J. Silicon alleviates the deleterious salt effect on tomato plant growth by improving plant water status. *J. Plant Physiol.*, 2006, 163(8): 847-855 (doi: 10.1016/j.jplph.2005.05.010).
62. Murillo-Amador B., Yamada S., Yamaguchi T., Rueda-Puente E., Ávila-Serrano N., García-Hernández J.L., López-Aguilar R., Troyo-Diéguez E., Nieto-Garibay A. Influence of calcium silicate on growth, physiological parameters and mineral nutrition in two legume species under

salt stress. *Journal of Agronomy and Crop Science*, 2007, 193(6): 413-421 (doi: 10.1111/j.1439-037X.2007.00273.x).
63. Artyszak A. Effect of silicon fertilization on crop yield quantity and quality — a literature review in Europe. *Plants*, 2018, 7(3): 54 (doi: 10.3390/plants7030054).
64. Vinogradova V.S., Martyntseva A.A., Kazarin S.N. *Zemledelie*, 2015, 1: 32-34 (in Russ.).
65. Bogomazov S.V., Levin A.A., Tkachuk O.A., Lyandenburskaya A.V. *Niva Povolzh'ya*, 2019, 3(52): 68-73 (in Russ.).
66. Lavoy I., Croy R., Hageman H. Relationship of nitrate reductase activity to grain protein production in wheat. *Crop Science*, 1970, 10(3): 280-285 (doi: 10.2135/cropsci1970.0011183X001000030021x).
67. Tao Z., Chang X., Wang D., Wang Y., Ma S., Yang Y., Zhao G. Effects of sulfur fertilization and short-term high temperature on wheat grain production and wheat flour proteins. *The Crop Journal*, 2018, 6(4): 413-425 (doi: 10.1016/j.cj.2018.01.007).
68. Khursheed M.Q. Effect of foliar application of Salicylic acid on growth, yield components and chemical constituents of Wheat (*Triticum aestivum* L. var. Cham 6). *5th Scientific Conference of College of Agriculture. Article Salahaddin University*. Erbil, 2011. Available: https://www.researchgate.net/publication/313968252. No date.
69. Janda T., Gondor O.K., Yordanova R., Szalai G., Pál M. Salicylic acid and photosynthesis: signalling and effects. *Acta Physiol. Plant*, 2014, 36: 2537-2546 (doi: 10.1007/s11738-014-1620-y).
70. Mokronosov A.T. *Ontogeneticheskii aspekt fotosinteza* [Ontogenetic aspects of photosynthesis]. Moscow, 1981 (in Russ.).