Analysis of morphobiological response of potato plants to treatment with silicon dioxide and molybdenum nanoparticles

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Abstract. The article presents the results of the effect of treating tubers and above-ground parts of the Kuzovok potato variety with SiO_2 and Mo nanoparticles on morphometric parameters and biochemical composition. It was found that treating seed potato tubers with SiO_2 0.18, Mo 0.045 g/kg increased germination energy on the 6th day regardless of the nanoparticle ratio (18 %, 13 % and 10 %, respectively). The concentration of SiO_2 0.18 g/kg and Mo 0.045 g/kg excludes long-term pre-planting light germination (vernalization) for 15-20 days. Biochemical analysis of potato tubers treated with Mo nanoparticles showed an increase in dry matter content (1.27 times at a concentration of 1 and 2 mg/m^2), starch (1.4 times at a concentration of 2 mg/m^2) and reduced sugars (2.6 times at a concentration of 4 mg/m^2). The highest potato yield (8.6 t/ha) was observed with combined treatment (tubers SiO_2 0.18 g/kg + Mo 0.045 g/kg and plants SiO_2 18 mg/m^2 + Mo 4 mg/m2), 21.8 % more than the control. Combined treatment reduced the incidence of tubers with stolon rot and common scab.

1 Introduction

In modern conditions, the urgent task of crop production development is to find means and methods to increase the yield of agricultural crops. Potatoes rank second in the world in terms of production volume after grain crops. The potato industry is an important component of the state program for the development of agriculture and regulation of the agricultural market [1].

The main areas of modern scientific research in potato growing include reducing pesticide loads, losses from pathogens and improving the quality of tubers.

Currently, the use of nanoparticles is a promising area in modern science and has practical applications in agriculture: for example, to increase crop yields, improve product quality, plant resistance to various infections, and reduce production costs [1]. In agriculture, nanomaterials are used in the form of fertilizers [2]. Nanofertilizers enhance

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physiological processes in plants and increase their stress resistance. The use of nanomaterials in agriculture reduces investments in the purchase of fertilizers and reduces the cost of operating vehicles.

Today, potato is one of the most widely cultivated crops in the world, which in a relatively short time produces a large amount of high-quality food per unit area. The use of ultrafine particles (UFP) of metals and non-metals [1] in agricultural production has the least polluting effect on the environment compared to modern analogues of fertilizers, since UFPs provide minimum requirements for the concentration used to treat plants and seeds. Each nanoparticle is a source of nutrition for plants.

According to a number of scientists [1-2], research in the field of UFPs has demonstrated that nanoparticles can directly affect plant cells and influence physiological processes, and stimulate plant growth and development, increasing crop yields.

Currently, practical research and use of molybdenum in agriculture occupies one of the leading places among other metal nanosolutions. There is no consensus in the literature on the effect of metal nanoparticles on physiological and biochemical processes in plants - both positive and negative effects from the use of colloidal nanosolutions are noted. Molybdenum is a good activator of antioxidant defense mechanisms of plants under stressful conditions. The toxicity of UFPs of metals is 10-40 times less than the toxicity of salts of the same metals.

Positive results were obtained in studies of corn, canola, tomatoes and capsicum after treatment with small doses of metal/metal oxide nanoparticles: TiO_2, Fe, SiO_2 [3].

Molybdenum has uneven distribution in plants. The production process is based on photosynthesis, but its relationship with productivity is not always clear, especially when exposed to UFP molybdenum. Photosynthetic activity of leaves is determined by the content of pigments - chlorophylls a и β. The main role of chlorophyll a in photosynthesis is to convert light energy into chemical energy. Chlorophyll β and carotenoids act as energy collectors.

Unfortunately, many available literary data on the use of UFP are difficult to compare both in doses, UFP size, and in the types of plants treated. At the same time, the importance of research into the use of UFPs in agriculture is obvious, since agricultural products form the basis of the country's food security [2].

In the last decade, special attention has been paid to the study of ultrafine particles of metal oxides [2]. Nanoparticles have many unique physical and chemical properties, such as extremely high specific surface area, increased chemical activity of atoms and molecules at the interfaces [3]. Nanoparticles have found wide application in the oil, chemical, aerospace, military, metallurgical and nuclear industries, agriculture, medicine due to their high strength, high corrosion resistance, low coefficient of thermal expansion and excellent thermal conductivity and electron conductivity. [4]. Nanoparticles can influence cellular processes, signal transmission and gene expression. They counteract active oxygen species, regulate water balance, enhance photosynthesis and nutrient absorption, and promote plant growth and productivity.

Nanoparticles have unique characteristics such as rapid and complete absorption by plants, which improves the quality and production of food products worldwide. Si nanoparticles generally have good bioavailability; easily penetrate the walls of plant cells [5]

More and more studies show that Si dioxide nanoparticles have the ability to enhance photosynthesis and plant biomass under stressful conditions; therefore, nanoparticles can be considered a new and effective source of energy [6]. The use of nanoparticles can increase crop yields, at the same time reduce the concentration of heavy metals in wheat [6], and rice [7].

The preparations are applied in microdoses and therefore do not pollute the environment. Copper, iron, and zinc nanoparticles have bactericidal properties and can complement and enhance traditional means of protection [8]. Silver nanoparticles also have antimicrobial properties and can be used as effective bactericidal materials due to their increased reactivity, due to their high surface/volume ratio [9]. Due to their high cost, nanoparticles are used only as seed treatment or when spraying crops with solutions to increase the effectiveness of interaction with plants. Researchers [10] have found a positive effect of Si nanoparticles on stress resistance, growth and development of potatoes.

2 Materials and methods

2.1 Location, soil and climate

Field studies were carried out in the peasant farm “Khomutskiy V.I.” in the village of Kubanka, Perevolotsky district, Orenburg region. The potato plants were treated with nanoparticles three times using a knapsack pump sprayer "Verve": in the phase of emergence, budding and flowering. The solution for treating the control group was prepared without adding nanoparticles. The experiments were laid on bare fallow. The soil of the experimental plot is slightly leached medium-humus (3.8 %) heavy loamy chernozem. The area of the plots is 10 m², fourfold replication, randomized placement.

2.2 Experimental scheme

The study of the effect of SiO_2 and Mo nanoparticles on the morphometric parameters and biochemical composition of potatoes was carried out in two stages. The object of the study was “Kuzovok” potato variety obtained in the potato breeding laboratory of the South Ural Research Institute of Horticulture and Potato Growing - branch of the Ural Federal Agrarian Research Center of the Ural Branch of the Russian Academy of Sciences. Nanoparticles produced by Plazmoterm were obtained by plasma-chemical synthesis. Nanoparticle suspensions were prepared according to TU 931800-4270760-96. Nanoparticles were dispersed in an ultra-dispersed bath "Sapphire TTC" frequency 35 kHz for 30 minutes. For this purpose, nanopowders were dissolved in an electrochemically activated catholyte with a pH of 7-9 and a redox potential of Eh = -400 – -500 mV, stabilized with the amino acid glycine at a concentration of 0.01 wt.%. Nanopowders were dissolved under a pressure of 9.8-14.7 Pa in a setup with a rotating drum with a drum rotation speed of 10 rpm, the processing time was 5 min. The concentration of Mo nanoparticles with a size of 80 nm was 16·10-4 mol/l and SiO_2 with a size of 25 nm – 6·10-3 mol/l.

Laboratory studies were conducted on seed material and potato plants treated with SiO_2 and Mo nanoparticles. Seed material not treated with nanoparticles and plants obtained from it were used as a control. The experimental design is presented in Table 1.

For disinfection, potato tubers were treated with a 0.01 % solution of potassium permanganate during their preparation for the experiment.

Potatoes were planted using a four-row GRUSE FL-20KLZ potato planter with a row spacing of 0.75 m and a semi-ridge sealing of tubers. The planting date in 2019 and 2021 was May 15, in 2020 - May 18. The plot area was 140 m^2, the accounting area was 70 m^2. The arrangement of samples in the repetition is systematic. When planting, the following tank mixture was added: Prestige (seed treatment) 1 l / t, Borogum (complex) 1 l / ha, Fitosporin AC 1 l / ha, Bionex-Kemi 40: 1.5: 2. Irrigation was carried out using a drum-type sprinkler system PRIMUS-2800П in 2019 and 2020. 10 and 8 irrigations were carried out with an irrigation rate of 270 to 600 m^3/ha, and a total water consumption of 4400 - 4750 m^3/ha.

Table 1. Experimental scheme.

Sample No.	Treatment	Concentration
Control		SiO_2 (0.0) + Mo (0.0)
1	potato tubers treatment (mg/kg)	Si O_2 (0.045) + Mo (0.045)
2		Si O_2 (0.09) + Mo (0.045)
3		Si O_2 (0.18) + Mo (0.045)
4	foliar treatment (mg/m^2)	SiO_2 (3) + Mo (1)
5		Si O_2 (6) + Mo (2)
6		Si O_2 (18) + Mo (4)
7	combined treatment, (mg/kg) / (mg/m^2)	Si O_2 (0.045) +Mo (0.045) / Si O_2 (3) + Mo (1)
8		Si O_2 (0.09) + Mo (0.045) / Si O_2 (6) + Mo (2)
9		Si O_2 (0.18) + Mo (0.045) / Si O_2 (18) + Mo (4)

Disease records were according to GOST 29267-91, GOST R 55329-2012, ELISA test, "Methodological guidelines for maintaining and studying the world potato collection" VIR (2010).

To determine the chlorophyll content, leaves were collected from the middle tier of the vegetative part of potatoes in the budding and flowering phases. The chlorophyll content was determined using the spectrophotometric method. The relevant standards and regulatory and technical documentation were used in the scientific research.

The material was assessed for biochemical composition in the quality laboratory of the A.G. Lorkh Federal Research Center of Potatoes.

All studies were conducted in accordance with the "Methodology for Research on Potato Crop" (1967), "International Classifier of the CMEA" (1984), "Methodological Recommendations for the Methodology of Conducting the Selection Process for Potato Crop" (1980).

3 Results

The study area is located in a zone with a sharply continental climate of temperate latitudes. The average monthly air temperature over three years of research fluctuates from - 24.3 to - 27.4°C in January, to +19.9...+22.4°C in July, the average annual temperature is +7.1°C. The average annual precipitation is 255-380 mm (Table 2).

Table 2. Main meteorological indicators during the years of the study.

Years of observation	Indicators					
	Average annual air temperature, °C	Maximum air temperature, °C	Precipitation, mm	Relative air humidity, %	Sum of positive temperatures (>0), °C	Sum of effective temperatures (>5)
2021	6.3	66	255	48	3820	2680
2022	5.7	60	372	56.6	3458	2386
2023	9.5	62	384	56.4	3695	2531
Standard	4.6	61.6	363	55.2	3163	2148

SiO_2 and Mo nanoparticles had a positive effect on the growth and development of tubers in a laboratory experiment.

4 Discussion

Treatment of seed potato tubers with SiO_2 and Mo nanoparticles increased the germination energy in all experimental groups. The germination energy on the 6th day was 10 % higher in tubers treated with nanoparticle solutions with a concentration of 0.045 g/kg, compared to the control. An increase in the concentration of SiO_2 nanoparticles caused an increase in the germination energy of tubers, the maximum difference with the control was 18 %. A similar pattern was observed on the 15th day of tuber germination. The number of sprouts on a tuber depended on the concentration of nanoparticles, was maximum at a SiO_2 concentration of 0.18 g/kg - 17.2 % higher than in the control.

The treatment of potato tubers with SiO_2 and Mo nanoparticle solutions had a more significant effect on the development of the root system. An increase in the SiO_2 concentration was accompanied by an increase in the number of roots. At a SiO_2 concentration of 0.18 g/kg, the number of roots was 1.52 times higher than in the control. Treatment of tubers with nanoparticle solutions had a smaller effect on the length of the roots. At SiO_2 nanoparticle concentrations in the solution of 0.045 and 0.09 g/kg, the length of the roots increased by 1.11 times, 0.18 g/kg - by 1.32 times.

The use of nanoparticle solutions allows to exclude long-term pre-planting light germination (vernalization) for 15-20 days.

Photosynthetic activity of leaves is determined by the content of pigments in them. Pre-planting treatment with solutions of SiO_2 and Mo nanoparticles contributed to an increase in the content of chlorophyll a and b. The dependence of the magnitude on the effect on the concentration of nanoparticles remains. The maximum concentration of SiO_2 in the solution increased the content of chlorophyll a and b by 53.3 and 4.5 %, respectively, compared to the control (Table 2).

Pre-planting treatment of tubers with solutions of SiO_2 and Mo nanoparticles increased potato yield compared to the control by 1.08 times using solutions with a concentration of SiO_2 and Mo nanoparticles of 0.045 g/kg, 1.12 times after using solutions with a concentration of SiO_2 and Mo nanoparticles of 0.09 and 0.045 g/kg, respectively, and 1.14 times when using solutions with a concentration of SiO_2 and Mo nanoparticles of 0.18 and 0.045 g/kg, respectively. This fact is associated not only with the improvement of morphophysiological parameters of plants, but also with a decrease in the incidence of stolon rot. In the control, 4.2 % of tubers were affected, in the experimental groups no affected tubers were found.

Combined treatment of potatoes (tubers with SiO_2 0.18 g/kg + Mo 0.045 g/kg and plants with SiO_2 18 mg/m^2 + Mo 4 mg/m^2) contributed to an increase in yield by 1.22 times (by 9.4 t/ha) compared to the control.

It was noted that after using SiO_2 and Mo nanoparticle solutions, there was no damage to tubers, with the exception of minor damage (1%) during foliar treatment of plants at a concentration of SiO_2 3 mg/m^2 + Mo 1 mg/m^2. As a result of treating potato tubers with Mo nanoparticle solutions at a concentration of 1, 2 and 4 mg/kg, the content of chlorophyll a and b increased by 52.0 and 40.2 %, respectively. When treating potato tubers with Mo nanoparticle solutions at a concentration of 2 and 4 mg/m^2, the content of chlorophyll b increased by 15.1 and 10.6 %, respectively; when treating with a concentration of 1 mg/kg, no significant differences were obtained compared to the control (Table 3).

Table 3. The effect of different concentrations of treatment of Kuzovok variety potato tubers with SiO_2 and Mo UFP on morphometric parameters.

Sample	Germination energy, %	Total number of sprouts per tuber, pcs.	Number of roots, pcs.	Root length, cm	Chlorophyll, mg/g raw weight	
					a	b
Control	70	8.7	6.7	3.8	1.19	0.30
1	75	9.3	7.9	4.2	1.26	0.38
2	78	9.6	8.8	4.2	1.30	0.44
3	88	10.2	10.2	5.0	1.34	0.46

Biochemical analysis of potato tubers treated with foliar solutions of Mo nanoparticles at a concentration of 1 and 2 mg/m^2 showed an increase in dry matter content by 1.27 times, i.e. the values varied by samples from 21 to 18.7 %. The quantitative content of starch after treatment with solutions of Mo nanoparticles at a concentration of 2 mg/m^2 increased to a maximum of 1.4 times compared to the control sample. As a result of treatment with solutions of Mo nanoparticles at a concentration of 4 mg/m^2, the amount of reduced sugars in plant tubers increased by 2.6 times compared to the control sample of the study and reached 0.28 %, while in the control experiment it was 0.03 % (Table 3).

The nitrate content in tubers treated with potato tuber nanoparticles in the 3rd sample, the NO_3 content exceeded the control sample by almost three times and amounted to 284 mg/kg, the other research samples differed from the control insignificantly.

The increase in chlorophyll content affected the obtained yield and marketability of potatoes, the maximum indicators (43.1 t/ha and 98.5 %) were observed in the second treatment sample and were significantly higher than in the control.

The maximum yield indicators (43.1 t/ha) and marketability (98.5 %) were observed in the 3rd treatment sample, which was higher than the control by 21.8 and 8.4 %, respectively.

The highest content of starch (14.2 %) and dry matter (19.3 %) in tubers was recorded in the 4th treatment sample (Table 4).

Table 4. Biochemical and economically valuable indicators of potato tubers treated with SiO_2 and Mo nanoparticles (average over 3 years of research).

Sample	Yield, t\ha	Marketability, %	Starch, %	Dry matter, %	Reduced sugar, %	NO_3, mg/kg
Control	33.7	90.2	12.5	17.8	0.06	198
1	35.1	90.1	13.0	18.6	0.06	165
2	37.2	89.8	13.1	19.1	0.07	176
3	37.6	88.9	13.3	18.7	0.07	154
4	40.9	98.1	13.6	18.9	0.05	120
5	41.7	97.9	13.5	18.8	0.07	124
6	43.1	98.5	13.6	18.9	0.06	138
7	34.2	97.3	14.0	19.1	0.05	105
8	34.1	97.4	14.2	19.3	0.07	110
9	34.0	96.8	14.1	19.4	0.07	100

The experimental data show an improvement in the qualitative and quantitative indicators of the variety with combined treatment with UFP, compared to the control.

5 Conclusion

Laboratory experiments on the study of morphometric indicators demonstrated that when treating seed potato tubers with SiO_2 0.18, Mo 0.045 (sample III), the germination energy on the 6th day exceeded the control, and in I and II samples by 18 %, 13 % and 10 %, respectively.

In laboratory experiments, biochemical analysis of the content of chlorophyll a and b in tubers of seed material of sample III exceeded the control, I, II samples by 12.6 ... 3.07 % and 53.3 ... 4.5 %, respectively.

As a result of field studies, the highest yield of Solanum tuberosum L was obtained with combined treatment (tubers SiO_2 0.18 g/kg + Mo 0.045 g/kg and plants SiO_2 18 mg/m^2 + Mo 4 mg/m2), while the yield values exceeded the control by 9.4 t/ha or 21.8 %.

Using ultrafine particles (UFP) SiO_2 + Mo in all samples, there was no infestation of tubers with stolon rot, common scab, with the exception of minor infestation (1 %) with foliar treatment of plants at a concentration of SiO_2 3 mg/m^2 + Mo 1 mg/m^2.

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References

1. V.K. Serderov, B.K. Atamov, D.V. Serderova, Influence of external environmental factors on the yield of promising potato varieties and hybrids in the conditions of the Republic of Dagestan, Priority scientific research in the field of production and processing of fruit and vegetable raw materials and grapes. Collection of scientific papers of the international scientific and practical conference, Makhachkala, 171-176 (2023)
2. W. Kuang, Y. Fan, Y. Chen, Structure and reactivity of ultrafine Ce–Mo oxide particles Catalysis Today, **68**, **1–3**, 75-82 (2001) https://doi.org/10.1016/S0920-5861(01)00293-0
3. G.D. Sun, K.F. Wang, C.-M. Song, G.-H. Zhang, A low-cost, efficient, and industrially feasible pathway for large scale preparation of tungsten nanopowders, Int. J. Refract. Met. Hard Mater., **78**, 100-106 (2019)
4. S. Guo-Dong, K.-F. Wang, X.-P. Ji, J.-K. Liu, H. Zhang, G. Zhang, Preparation of ultrafine/nano Mo particles via NaCl-assisted hydrogen reduction of different-sized MoO_2 powders, International Journal of Refractory Metals and Hard Materials, **80**, 243-252 (2019) https://doi.org/10.1016/j.ijrmhm.2019.01.020
5. M. Rizwan, S. Ali, M.Z. Rehman, S. Malik, M. Adrees, M.F. Qayyum, S.A. Alamri, M.N. Alyemeni, P. Ahmad, Effect of foliar applications of silicon and titanium dioxide nanoparticles on growth, oxidative stress, and cadmium accumulation by rice (Oryza sativa Acta Physiol. Plant., **41**, 35 (2019) https://doi.org/10.1007/s11738-019-2828-7
6. A. Hussain, M. Rizwan, Q. Ali, S. Ali, Seed priming with silicon nanoparticles improved the biomass and yield while reduced the oxidative stress and cadmium concentration in wheat grains Environ, Sci. Pollut. Res. Int., **26**, 7579-7588 (2019) https://doi.org/10.1007/s11356-019-04210-5

7. C. Wang, H. Rong, X. Zhang, W. Shi, X. Hong, W. Liu, T. Cao, X. Yu, Q. Yu, Effects and mechanisms of foliar application of silicon and selenium composite sols on diminishing cadmium and lead translocation and affiliated physiological and biochemical responses in hybrid rice (Oryza sativa L.) exposed to cadmium and lead, Chemosphere, 251 (2020) https://doi.org/10.1016/j.chemosphere.2020.126347
8. Yu.O. Ponomarev, A.G. Prudnikova, A.D. Prudnikov, Quality of red clover feed when treating seeds with metal nanopowders, Agrochemical Bulletin, **5**, 42-44 (2017)
9. E.A. Azhmuldinov, M.A. Kizaev, M.G. Titov, The effect of chitosan, ultrafine silver particles and their complex on the rumen content of cattle Veterinary doctor, **6**, 11-15 (2020)
10. E.V. Bezruchko, L.S. Fedotova, Silicon available for plants is a factor in sustainable potato production, Agrochemistry, **8**, 70–81 (2021)
11. Yu.D. Smirnova, E.A. Podolyan, Use of nanosized preparations to optimize microclonal propagation of potatoes Agrarian scientific journal, **1**, 51-55 (2024)
12. E.V. Zorin, Peculiarities of the influence of pre-planting treatment of potato tubers with ultra-dispersed powders and salts of iron and copper on their yield properties: Diss. ... Cand. of Agricultural Sciences: 06.01.09, Moscow, 124 (2004)