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Effects of Silicon Dioxide Nanoparticles on Biological and Physiological Characteristics of *Medicago sativa L. nothosubsp. varia (Martyn)* in Natural Agroclimatic Conditions of the Subtaiga Zone in Western Siberia

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Abstract This study is aimed at investigating effects of pre-sowing seed treatment of *Medicago sativa L. nothosubsp. varia* (*Martyn*) *Arcang.*, *Sarga* variety, with SiO_2 nanoparticles produced by laser ablation in a liquid. The purpose of the study is to investigate effects of suspensions of silicon dioxide nanoparticles at different concentrations on biological and physiological characteristics of *M. sativa L. nothosubsp. varia* in natural agroclimatic conditions of the subtaiga zone in Western Siberia. The study has shown that the pre-sowing seed treatment of *M. sativa L. nothosubsp. varia* (*Martyn*) *Arcang.*, *Sarga* variety, with silicon dioxide nanoparticles at different concentrations has a stimulating effect on contents of chlorophyll, carotenoids, and non-steroidal phytoestrogens in a vegetative part of the plant, as well as biometric and morphometric parameters, yield, and phytoremediation potential. It has been established that *M. sativa* is hypersensitive to the studied pre-sowing seed treatment with suspensions of SiO_2 nanoparticles at different concentrations, which determines the specificity of changes in physiological parameters, including increase in contents of photosynthetic pigments, isoflavonoids, and hydroxycinnamic acids in the plant exposed to suspensions of SiO_2 nanoparticles. A significant increase in the content of biologically active substances under the influence of SiO_2 nanoparticles indicates the high sensitivity of *M. sativa* and the specific role of nanoparticles in stimulating the biosynthesis of biologically active substances. The findings of the study demonstrate that pre-sowing seed treatment of *M. sativa L. nothosubsp. varia* (*Martyn*) *Arcang.*, *Sarga* variety, with ultrafine silicon dioxide nanoparticles at different concentrations, had a stimulating effect on biological and physiological characteristics of *M. sativa L. nothosubsp. varia* (*Martyn*) *Arcang.*, *Sarga* variety.

Keywords Silicon dioxide nanoparticles · *Medicago sativa* · Natural agroclimatic conditions · Agricultural landscape · Yield · Biologically active substances

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1 Introduction

The study of silicon oxide influence on agricultural crops and biomass formation of plants started in the mid-nineteenth century from long-term experiments of the Rothamsted Experimental Station, where systematic field research was conducted. Si was classified as a biophilic element in 1922. The silicon content in plants is comparable with content of basic macronutrients. Dry weight of plants contains 1–2% Si, while their ashes contain from 20 to 91% Si. A higher stage of evolutionary development of a plant is associated with a lower Si content [1].

Study regarding the silicon influence on agricultural crops, especially influence of biologically active substances in

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colloidal state (SiO_2 nanoparticles), is very promising. There are many research works that prove that biophilic elements in colloidal state (nanoparticles), including nanoparticles of silicon oxide, have a stimulating effect on the growth of plants [2–5]. Increase in stability and yield of plants was observed 1.5–2 times as much on average for practically all agricultural crops (potatoes, cereal crops, vegetables, fruits) and technical plants (cotton, flax). The downside of the nanotechnology introduced into agriculture is associated with its impact on the environment, soil, water, and agricultural landscape that has been poorly studied so far. A disadvantage of many research works is carrying out research in the laboratory conditions where the plants were grown in limiting conditions (experiments duration, medium, vessels) without taking into account natural agroclimatic conditions.

The purpose of the study is to investigate the effect of silicon dioxide nanoparticle suspensions at different concentrations on biological and physiological characteristics of *Medicago sativa L. nothosubsp. varia* in natural agroclimatic conditions of the subtaiga zone in Western Siberia.

2 Experiments

The study was conducted both in vitro (pot experiment) and in vivo (field experiments) in facilities of the Siberian Research Institute of Agriculture and Peat, Branch of the Siberian Federal Research Center, Russian Academy of Sciences.

2.1 Materials

As a plant material to study the influence of suspensions of silicon dioxide nanoparticles at different concentrations, *M. sativa L. nothosubsp. varia* (*Martyn*) *Arcang*., *Sarga* variety, introduced in conditions of Tomsk region, was chosen.

The agrochemical properties of initial soil samples prior to sowing (spring period) have the following parameters: pH = 4.6 (hydrolytic); Wav. =22.6%, Kw −1.22; organic substance composition in soil samples—5.01; Si content—48.8%; $N\text{-}NH_4$ ions—4.3 mg/100 g of soil; $N\text{-}NO_3$ (nitrate nitrogen)—11.5 mg/100 g of soil; P_2O_5 content—506.53 mg/100 g of soil; K_2O—169.7 mg/100 g of soil. Analyses of soil samples showed contamination of soil with heavy metals: Zn—251.87 mg/kg; Cd—2.94 mg/kg; Pb—11.29 mg/kg; Cu—21.06 mg/kg.

To conduct the studies, suspensions with silicon dioxide (SiO_2) nanoparticles were used. The average size of particles was 7 nm; mass concentration of particles in suspension was 30 mg/L. Particles were characterized by oxygen deficiency in comparison with ideal structure of SiO_2 and imperfective with insignificant amount of carbon on their surface as a result of interaction with carbon dioxide.

2.1.1 Chemicals and Reagents

All chemicals, reagents, and solvents used in this research were high purity analytical grade. During spectrophotometric analyses of isoflavonoids and hydroxycinnamic acids, distilled water and ethanol at different concentrations (95, 70, 50%) were used. Analytical standards—ononin, USP (USA)—caffeic acid were taken from Sigma-Aldrich (Germany) and used as standards of comparison.

2.1.2 Methods and Instrumentation

The field experiment was based on the method proposed by B.A. Dospekhov (small-plot experiments) in natural agroclimatic conditions [6]. The experiment was designed with systematic distribution of variants and three replications. Plant samples were taken at different phenophases of *M. sativa* in budding and maturation stages. Soil sampling was carried out prior to sowing and at the end of the growing period of the plant. Soils were sampled in accordance with the applicable soil sampling requirements and the guidelines for agrochemical inspection of agricultural soils [7].

For the purpose of the study, suspensions with SiO_2 nanoparticles were produced by pulsed laser ablation with nanosecond infrared laser irradiation of target monocrystalline silicon in distilled water [8]. For seeds, treating suspension of SiO_2 was used. The seeds were sprayed with dispersed suspensions of SiO_2 nanoparticles at concentrations of 3, 1.5, and 0.3 mg/L (1 mL/10 kg, dry treatment) and then mixed for 3–5 min to ensure uniform wetting of seed surfaces. Seeds were dried for 6 h at 23 ± 1 °C. The control variants of the experiments were not treated. The experimental variants were neither scarified nor inoculated. Sowing was performed 24 h after the treatment.

The silicon content in soil and plant samples was determined by the AGILENT 4100 microwave plasma-atomic emission spectrometer (atomic emission spectroscopy method of measurement). The calibration curve was plotted using a state reference sample. The samples were decomposed in concentrated acids—5 mL nitric acid, 5 mL hydrochloric acid, and 3 mL hydrofluoric acid. The decomposition of samples was carried out in the Speedware four microwave system.

- The chlorophyll content was analyzed in an alcoholic extract using the UV-1601 spectrophotometer manufactured by SHIMADZU (Japan) at the wavelength of 665, 649, and 440.5 nm and then calculated by Vernon's formulas [9].
- Contents of heavy metals in soil and plant samples were analyzed in the certified laboratory and analytical center of the Siberian Research Institute of Agriculture and Peat [10, 11].

Determination of isoflavones and hydroxycinnamic acids was performed on a spectrophotometer SF-2000 at the following wavelengths: for isoflavones, 260 ± 2 nm; for hydroxycinnamic acids, 325 ± 2 nm; in terms of absolutely dry raw material (%) E (%) for hydroxycinnamic acids - of 2.21% for isoflavones is 1.82% [12, 13].

2.1.3 Statistical Analysis

Obtained data were processed with the statistical software package "Statistics for Windows 6.0". Validity of the results was tested by Mann-Whitney *U* test.

3 Results and Discussion

3.1 Effects of Silicon Dioxide Nanoparticles on Biological Characteristics of *Medicago sativa*

The primary natural response of any plant to the exposure is expressed in a change in its habit, biometric, and morphometric parameters, as well as behavior at different phenophases of its ontogenesis (individual development of a plant). According to the available literature [14], silicon accelerates maturation of maize and germination of barley and rice seeds by 2–2.5 weeks, increases root mass of barley, enhances photosynthesis and growth of rice plants, accelerates ripening of rice, and has beneficial effects on nitrogen, phosphate, and potassium metabolism. It enhances plant drought resistance, resistance of plants to fungal diseases, pests, lodging, and low temperatures, which is confirmed by our study.

The first individual seedlings appeared in the experimental variant with the pre-sowing seed treatment with 1.5 mg/L suspension. Seedlings in the control variant and other experimental variants appeared only after 10 days. In terms of plant population, there were not any significant differences between the control variant and experimental variants.

The analysis of morphometric parameters of *M. sativa* shows that the pre-sowing seed treatment with suspensions of SiO_2 nanoparticles at concentrations of 0.3 and 1.5 mg/L has a stimulating effect on height of the plants (Table 1). Treatment with SiO_2 nanocolloids at the concentration of 1.5 mg/L has a positive effect on tillering of *M. sativa*. Number of *M. sativa* leaves in all experimental variants increased. A significant increase was observed in the variant with 0.3 mg/L (Table 1).

The pre-sowing seed treatment with suspensions of silicon dioxide nanoparticles had a positive effect on yield in the experimental variant with 1.5 mg/L SiO_2 suspension, while concentrations 3 and 0.3 mg/L decreased yield by 5–13%.

In all variants where seeds were treated with suspensions of silicon dioxide nanoparticles, except for the variant at the minimum concentration of 0.03 mg/L, fresh and dry masses of roots were significantly higher than those in the control variant (Table 1).

3.2 Effects of Silicon Dioxide Nanoparticles on Physiological Characteristics of *Medicago sativa L. nothosubsp. varia* (*Martyn*) *Arcang*., *Sarga* Variety

3.2.1 Si Content

Based on the histochemical analysis performed by the authors [13], it can be concluded that silicon in roots is evenly distributed throughout the tissue, although some scientists [14–16] believe that it is concentrated in the epidermal tissues and coronary cells. In transpiration organs, including leaves, silicon is localized in the epidermal tissues where it forms a double cuticular silicon layer and prevents plants from excessive evaporation and penetration of fungal hyphae.

A histochemical analysis of the plant was beyond the scope of our study. It was important to carry out a comparative analysis of silicon accumulation potential of the plant in natural agroclimatic conditions after the pre-sowing seed treatment with suspensions of silicon dioxide nanoparticles in different concentrations.

As can be seen from the presented data (Table 2), the treatment with 3 and 0.3 mg/L suspensions of silicon dioxide nanoparticles increases the accumulation capacity of *M. sativa* in all organs of the plant. The Si content in organs of the plant grew by 3–11.4% at the concentration of 3 mg/L and by 7–20% at the concentration of 0.3 mg/L. The treatment with 1.5 mg/L suspension of silicon dioxide nanoparticles reduces the Si content in the leaves and a stem of the plant (6.2–34.5%) and slightly increases the Si content in the root system (3.7%).

Silicon is important for acidic soils that are rich in aluminum. Soluble Si is primarily absorbed on Al and Fe hydroxides, reduces their activity and prevents them from entering into the plant. On the other hand, Al and Fe oxides reduce assimilation of Si by plants. The broader the SiO_2: R_2O_3 ratio in the soil, the higher the rate of Si absorption by plants.

Perhaps, the effect of soil pH on amount of Si absorbed by plants is associated with contents of Al and Fe oxides: the maximum amount of absorbed Si is observed at neutral and subacid reactions of soil [17], which is confirmed by our study. The Si content in organs of plants is found to increase at soil pH_{av} = 6.7 in the autumn season.

3.2.2 Content of Biologically Active Substances

For plant diagnostics, physiological and biochemical parameters of assimilated organs are used. These parameters

Table 1 Effect of pre-sowing treatment of *M. sativa* seeds with suspensions of silicon dioxide nanoparticles on biometric parameters of plants and yield of the vegetative mass

Variant of the experiment	Plant height, cm	Number of stems per plant	Wet weight of green mass, g	Dry weight of green mass, g	Wet weight of root mass, g	Dry weight of root mass, g
Control variant (without treatment)	46.3 ± 2.0	3.33 ± 0.3	26.67	10.38	5.28	1.33
SiO_2 3 mg/L	44.0 ± 4.8	2.67 ± 0.3	22.00	10.00	6.77	1.61
SiO_2 1.5 mg/L	48.8 ± 0.9	3.67 ± 0.4	27.83	13.53	7.60	1.83
SiO_2 0.3 mg/L	48.2 ± 3.2	2.00 ± 0.6	25.33	10.34	4.13	1.18

determine growing and reproductive processes to a considerably degree and are sensitive to environmental changes [16].

The chemical composition of *M. sativa* is represented by a set of biologically active substances. The prevailing biologically active substances include isoflavonoids, hydroxycinnamic acids, chlorophylls, proteins, and amino acids, including essential ones, vitamins, macro- and micronutrients.

The mechanism of silicon participation in plant metabolism has not yet been completely clarified [1]. However, it is supposed to be associated with a change in activities of enzymes. For example, silicon is likely to inhibit invertase and acid phosphatase in rice plants [18].

As can be seen from the presented data (Table 3), the treatment with 1.5 mg/L suspension of silicon dioxide nanoparticles increases the content of isoflavonoids and hydroxycinnamic acids in the aerial portion of *M. sativa* only by the end of the vegetative period, as compared to that of the control variant. This trend is clearly shown for both 40 and 70% ethanol used as an extractant. The content of isoflavonoids and hydroxycinnamic acids increases by 14–29% in case of 40% ethanol and 20–40% in case of 70% ethanol. The treatment with 3 and 0.3 mg/L suspensions of silicon dioxide nanoparticles significantly increases the content of isoflavonoids in grasses of *M. sativa* by 39–60% in the samples taken on August 14, 2015 and by 4–60% in the samples taken on October 8, 2015. The similar trend was observed for hydroxycinnamic acids: their content decreased by 35–57% in the samples taken on October 8, 2015 and by 14–71% in the samples taken on August 14, 2015.

Table 2 Effects of suspensions of SiO_2 nanoparticles on the Si content in organs of *M. sativa*

Treatment	Mass fraction of silicon, %		
	Leaves	Stem	Root
Control variant (without treatment)	0.55	0.65	0.79
SiO_2 3 mg/L	0.48	0.67	0.88
SiO_2 1.5 mg/L	0.36	0.61	0.82
SiO2 0.3 mg/L	0.59	0.78	0.90

The increased content of isoflavones and hydroxycinnamic acids in aerial parts of *M. sativa* only by the end of the vegetative period is likely to be explained by the fact that the Si content in plants has reached its maximum by the end of the vegetative period [19]. The study also shows a correlation between Si accumulation in aerial parts of *M. sativa* and estrogen-like activity of isoflavones and hydroxycinnamic acids in the grass of *M. sativa* after treatment with suspensions of SiO_2 nanoparticles. The experimental results show that the increased silicon content in the aerial organs of the plant inhibits an estrogen-like activity of isoflavonoids and hydroxycinnamic acids, while the decreased silicon content in the aerial organs of the plant leads to a higher content of isoflavonoids and hydroxycinnamic acids.

One of the biochemical indicators of plant reaction on environmental changes and degree of their adaptation to the new conditions is chlorophyll content and carotenoids—the main photoreceptors of a photosynthetic cell [16, 20, 21].

- The analysis of chlorophyll data shows that the pre-sowing seed treatment of *M. sativa* with 3, 1.5, and 0.3 mg/L suspensions of silicon dioxide nanoparticles increased the content of photosynthetic pigments in the grass of *M. sativa* from 51 to 92.5% in all experimental variants as compared to that of the control variant: chlorophyll α increased by 9.65–12.82 mg/g (control variant—6.69 mg/g); chlorophyll β by 2.75–3.79 mg/g (control variant—1.87 mg/g); and carotenoids by 2.75–4.06 mg/g (control variant—2.29 mg/g).
- The data on increased green mass of *M. sativa* and biometric parameters suggest that the enhanced habit of the plant after the pre-sowing treatment of *M. sativa* seeds with suspensions of SiO_2 nanoparticles leads to increased transpiration activity of the plant and, therefore, increased content of chlorophyll α, β, and carotenoids. This effect is confirmed by studies of other authors [2–5], where they mentioned that increase in photosynthetic pigments occurs due to the influence of nanoparticles. In several works [16, 20, 22, 23], it is noted that stimulating effect on formation

Table 3 Content of isoflavonoids and hydroxycinnamic acids in *M. sativa*, %

Name of a sample, date of sampling	Variant/extractant	Isoflavonoids		Hydroxycinnamic acids	
		40% ethanol	70% ethanol	40% ethanol	70% ethanol
M. sativa (grass) August 14, 2015	1	0.505	0.720	0.903	1.194
	2	0.428	0.286	0.768	0.511
	3	0.445	0.471	0.781	0.833
	4	0.360	0.440	0.636	0.770
M. sativa (grass) October 08, 2015	1	0.453	0.404	0.932	0.869
	2	0.218	0.163	0.436	0.254
	3	0.583	0.567	1.061	1.038
	4	0.435	0.194	0.797	0.366
M. sativa (root) October 08, 2015	1	0.161	0.146	traces	traces
	2	0.162	0144	traces	traces
	3	0.163	0.141	traces	traces
	4	0.123	0.130	traces	traces

of photosynthetic pigments has weak influence on a pigment system. According to the principle of multiple adaptations, the pigment system is formed effectively in case of presence of primary adaptive reactions [24, 25].

3.2.3 Change in Contents of Heavy Metals in the Soil

The use of silicon compounds for plant protection has some agroecological aspects: a decreased pesticide load in agrocenoses [24], a limited release of xenobiotics to the environment, increased resistance of plants to mutations due to the fact that the Si-OC bond is stronger than P-O-C in DNA and RNA [26].

As a part of the field study, the agrochemical analysis was carried out in the selected plot. Initial agrochemical properties of the soil before seeding (spring season): hydrolytic pH_{av}—4.6; W_{av}—22.6%, K_w—1.22; average organic matter content in the soil $_{av.}$—5.01; Zn—251.87 mg/kg; Cd—2.94 mg/kg, Pb—11.29 mg/kg; Cu—21.06 mg/kg; Si—48.8%, $N\text{-}NH_4$ (metabolic ammonium)—4.3 mg/100 g of soil; N-NO3 (nitrate nitrogen)—11.5 mg/100 g of soil; P_2O_5 (movable phosphorus compounds)—506.53 mg/100 g of soil; and K_2O (movable potassium compounds)—169.7 mg/100 g of soil.

The data on changed contents of heavy metals in the soil are presented in Table 4. As follows from the data presented in the Table 4, the treatment with 1.5 and 0.3 mg/L suspensions of silicon dioxide nanoparticles reduces the Zn content in the soil and increases the content of heavy metals, such as Pb and Cu, in relation to the control variant. Across all experimental variants, the Zn content increased by 7.15–78%, while Pb and Cu contents increased by 12–219 and 14–57%, respectively. The treatment with 3 mg/L suspension of silicon dioxide nanoparticles reduces the Cu content by 7.1%.

Absorption of heavy metals by the soil largely depends on a reaction of a medium and type of anions that prevail in a soil solution [27]. An acid medium tends to absorb copper (Cu), lead, and zinc (Zn) to a greater extent. In our study, the treatment with 1.5 and 0.3 mg/L suspensions of silicon dioxide nanoparticles reduced the Zn content in the soil.

Changes in agrochemical parameters, such as $N\text{-}NH_4$ (metabolic ammonium), N-NO3 (nitrate nitrogen), and K_2O (movable phosphorus compounds) will be described in the next study. This study focuses on changes in heavy metal contents.

The comparative analyses of the initial agrochemical soil parameters for the spring season and final data for the vegetative period in autumn show that the treatment with 1.5 and 0.3 mg/L suspensions of silicon dioxide nanoparticles reduces the Zn content in the soil by 25–43%.

In many research works, it was shown that there is a certain connection between chemical and elemental composition of the soil, but the direct dependence of heavy metal content in plants and in soils was not observed because of the selective

Table 4 Effects of suspensions of SiO_2 nanoparticles on contents of heavy metals in the soil, mg/100 g of the soil, W_{av}—26.02, pH_{av}—6.7 (date of sampling: August 14, 2015)

Treatment	Heavy metals			
	Zn	Cd	Pb	Cu
Control variant (without treatment)	429.9	0.13	9.02	23.1
SiO_2 3 mg/L	458.1	0.13	10.11	21.42
SiO_2 1.5 mg/L	190	0.13	10.58	26.41
SiO_2 0.3 mg/L	107	0.13	28.85	36.19

Table 5 Effects of suspensions of SiO_2 nanoparticles on heavy metal contents in organs of *M. sativa*

Heavy metals	Treatment	Organ		
		Leaves	Stem	Root
Zn	Control variant (without treatment)	14.33	12.68	19.05
Cd		0.005	0.005	0.005
Pb		1.01	0.67	0.19
Cu		2.89	1.68	1.85
Zn	SiO_2 3 mg/L	22.78	24.17	15.87
Cd		0.005	0.005	0.005
Pb		0.40	0.12	0.29
Cu		4.43	4.08	3.29
Zn	SiO_2 1.5 mg/L	20.43	9.06	13.28
Cd		0.005	0.005	0.005
Pb		1.59	0.91	0.33
Cu		1.28	1.94	1.87
Zn	SiO_2 0.3 mg/L	22	12.31	7.71
Cd		0.005	0.005	0.012
Pb		0.44	0.29	0.42
Cu		7	4.6	3.79

ability of plants to accumulate elements in required quantity [28, 29]. Probably, there are genetic and ecological factors that influence the elemental composition of plants, and their priority is changing depending on environmental conditions, e.g., at the anthropogenic impact on the environment becomes prevalent [28].

The organic matter level in the soil is one of the most important homeostasis parameters of soil fertility. The comparative analysis of agrochemical soil parameters for the spring and autumn seasons shows that the treatment with 1.5 and 0.3 mg/L suspensions of silicon dioxide nanoparticles contributes to the growth of the organic matter content in the soil by 14–19%.

The agrochemical studies of the soil in the experimental plot demonstrated that the experimental plot was contaminated with heavy metals. In this connection, we determined heavy metal contents in the plant and analyzed the effects of the pre-sowing seed treatment with suspensions of silicon dioxide nanoparticles on accumulation and distribution of heavy metals in organs of the plant, as well as the phytoremediation potential.

3.2.4 Heavy Metal Contents in Organs

During the detection of heavy metal content in organs of plants, the influence of pre-sowing treatment with suspensions of SiO_2 nanoparticles on accumulation and translocation of heavy metals in *M. sativa* organs and phytoremediation potential of plant was analyzed. We think that the study of influence of heavy metal content in organs of plants is an essential part in complex estimation of pre-sowing treatment of seeds with dispersed suspensions of SiO_2. It is known that accumulation of heavy metals in plants depends on their species affiliation, physical-chemical properties of metal, and type of pollutant [30].

The data on heavy metal accumulation by organs of the plant are presented in the Table 5. As follows from the presented data (Table 5), the pre-sowing seed treatment with suspensions of silicon dioxide nanoparticles at all concentrations (3, 1.5, and 0.3 mg/L) increases the Cu content (as compared to that of the control variant) in organs of *M. sativa* at the end of the vegetative period. The maximum Cu content in organs of the plant is observed for 3 and 0.3 mg/L suspensions: 53–143% in the leaves, 143–174% in stems, and 78–103% in roots. In addition, the treatment with 3, 1.5, and 0.3 mg/L suspensions increases the Zn content by 43–59% in the leaves of *M. sativa*, while the treatment with 3 mg/L suspension increases the Zn content by 91% in stems of *M. sativa*.

The treatment with 1.5 mg/L suspension had a certain effect on Pb accumulation. In this case, the Pb content increased in all organs of the plant as compared to that of the control variant by 57% in the leaves, 36% in stems, and 74% in roots. The increased Pb content (by 21–53%) in the root system was also identified when treated with 3 and 0.3 mg/L suspensions.

1.5 mg/L suspension of SiO_2 in water (Table 5) had an effect on cadmium (Cd) accumulation capacity of the root system of *M. sativa*: by the end of the vegetative period, the Cd content in the root system increased by 140% as compared to that of the control variant.

Cd is one of the toxic pollutants of the environment [31]. This element is characterized by high mobility in soil and quick entry to plants [32]. Accumulating in plant organs and

Table 6 Effects of the pre-sowing treatment of *M. sativa* seeds with suspensions of silicon dioxide nanoparticles on the coefficient of biological absorption (CBA) and the translocation coefficient (TC) in the bearing phase

Treatment	Coefficient of biological absorption (CBA) heavy metals				Translocation coefficient (TC) heavy metals			
	Zn	Cd	Pb	Cu	Zn	Cd	Pb	Cu
Control variant (without treatment)	0.05	0.08	0.18	0.19	1.41	2	8.8	2.47
SiO_2 3 mg/L	0.1	0.08	0.4	0.05	2.96	2	1.79	2.59
SiO_2 1.5 mg/L	0.16	0.08	0.24	0.12	2.22	2	7.58	1.72
SiO_2 0.3 mg/L	0.32	0.08	0.03	0.9	4.76	0.83	1.74	3.06

tissues, it has a negative effect on the metabolism and productivity of plants.

3.2.5 Phytoremediation Potential of Soils Contaminated with Heavy Metals Cd, Pb, Cu, and Zn

In order to describe the migration of chemical elements in agricultural landscapes, it is important not only to study the living matter through a number of complex geochemical parameters, such as biomass and annual production, but also to determine its content, as well as the intensity in which individual chemical elements are involved in the biological cycle. The universal indicators that describe the intensity of biological absorption in landscapes are coefficients and series of biological absorption.

Effects of biophilic elements on these universal indicators that describe the intensity of biological absorption in agricultural landscapes are of great interest to researchers.

The coefficient of biological absorption (CBA) for *M. sativa* in relation to Cd, Cu, Pb, and Zn was calculated on the basis of the data on heavy metal contents in the soil and organs of the plant.

The coefficient of biological absorption is the ratio of the content of an element in the aerial part to its gross content in the soil: $CBA = C_P/C_S$, where C_p is the content of elements in plant ash (aerial part). The translocation coefficient (TC) is the ratio of the content of an element in the aerial part to its content in the roots: $TC = C_P/C_R$.

The pre-sowing seed treatment with suspensions of silicon dioxide nanoparticles significantly increased both the coefficient of biological absorption and the translocation coefficient. Table 6 shows that the treatment with 3, 1.5, and 0.3 mg/L suspensions of SiO_2 increases the coefficient of biological absorption and the translocation coefficient in relation to zinc by several times (CBA by 1–6.4 times; TC by 57%–3.3 times) as compared to those of the control variant. In relation to copper, 0.3 mg/L suspension increases CBA by 4.7 times and TC by 1.2 times. It should be noted that the increase in CBA in relation to Cu is accompanied by a decrease in CBA in relation to Pb (by 6 times as compared to that of the control variant). In its turn, the increase in CBA in relation to Pb when treated with 3 and 1.5 mg/L water suspensions is accompanied by a decrease in CBA in relation to Cu (by 1–3.8 times).

The highest coefficients of biological absorption and translocation coefficients for *M. sativa* (CBA = 0.9, TC = 3.06) were identified in relation to copper. This demonstrates a high accumulation capacity for this metal in the biomass of the test plant, as well as the capability to translocate copper from the roots to aerial organs.

The treatment with 0.3 mg/L suspension of SiO_2 significantly improved the phytoremediation potential of *M. sativa* in relation to copper in the sod-podzolic soil in natural agroclimatic conditions of the subtaiga zone in Western Siberia.

4 Conclusion

Our study has proved that the pre-sowing seed treatment of *M. sativa L. nothosubsp. varia* (*Martyn*) *Arcang.*, *Sarga* variety, with silicon dioxide nanoparticles at different concentrations has a stimulating effect on contents of chlorophylls, carotenoids, and non-steroidal phytoestrogens in a vegetative part of the plant, as well as biometric and morphometric parameters, yield, and phytoremediation potential.

It has been established that *M. sativa* is hypersensitive to the studied pre-sowing seed treatment with suspensions of SiO_2 nanoparticles at different concentrations, which determines the specificity of changes in physiological parameters, including increase in the content of photosynthetic pigments, isoflavonoids, and hydroxycinnamic acids in the plant exposed to suspensions of SiO_2 nanoparticles.

The findings of the study demonstrate that the pre-sowing seed treatment of *M. sativa L. nothosubsp. varia* (*Martyn*) *Arcang.*, *Sarga* variety with dispersed suspensions of silicon dioxide nanoparticles at different concentrations has a stimulating effect on biological and physiological characteristics of *M. sativa L. nothosubsp. varia* (*Martyn*) *Arcang.*, *Sarga* variety in natural agroclimatic conditions of the subtaiga zone in Western Siberia.

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