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Silicon Nanoparticles Synthesized by Pulsed Plasma in Liquid and Their Effect on Grain Growth

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Abstract: *Silicon nanoparticles (SiNPs) were synthesized from silicon ingots using pulsed plasma in a water-ethylene solution with varying ethylene concentrations (10%, 40%, 70%, and 90%). X-ray diffraction analysis confirmed the formation of pure-phase silicon, and scanning electron microscopy revealed rod-shaped nanostructures with an average length of 40 nm. These synthesized SiNPs were evaluated for their effects on the growth and development of barley and wheat grains. Key growth parameters—germination rate, shoot height, and root length—were measured and compared with control samples. Results showed that barley exhibited a higher germination rate and greater shoot height than wheat. Interestingly, as the concentration of SiNPs increased, both barley and wheat developed shorter but stronger and more upright roots compared to controls. This structural change suggests enhanced resistance to environmental stress. Overall, the study demonstrates that silicon nanoparticles can positively influence grain crop development, offering potential for agricultural applications aimed at improving plant strength and resilience under challenging conditions.*

Keywords: silicon nanoparticle; pulsed plasma; plant.

1. INTRODUCTION

Silicon nanoparticle has been widely used in recent years in medicine [1], agriculture as a fertilizer [2], plant pests [3] and in the production of lithium-ion batteries [4]. The element Silicon occupies 27.7 % of the earth's crust and is not found in its pure form. Recently, a method for the chemical production of silicon nanoparticles from silicon compounds has been developed [5]. A vegetable peeler, a rice stalk are widely used for the chemical production of silicon nanoparticles [6]. Silicon nanoparticles have been studied over the past decade and are of growing interest due to their special physical properties, active surface layer, distinctive photoluminescence and biocompatibility. Their use is widely increasing in the field of energy and electronic engineering. The direction of chemical extraction of silicon from rice husks is the most convenient and does not require large costs, extracting it from unused rice husks for use as fertilizer, pesticide, soil is being studied. In Kyrgyzstan, the volume of rice and wheat grain cultivation is higher than that of other grain products [7]. Silicon nanoparticle is the main physiological feature when applied to plants and affects the metabolic activity of plants [8]. The mesoporous nature of silicon nanoparticles makes them good candidates as suitable nano-carriers for various molecules that can help in agriculture [9].

There are many methods for the synthesis of nanoparticles. Among them are sol-gel [10], biological synthesis [11] and the pulsed plasma in liquid [12,13]. Nanoparticles are obtained by the sol-gel method in several stages: hydrolysis, condensation, drying and calcification. The pulsed plasma in liquid method is an inexpensive, environmentally friendly and simple method. It differs from other synthesis methods in that it does not require the creation of different conditions, unlike other methods. Silicon nanoparticle has recently been used in many fields, however, applications in agricultural crops are very limited. In this research, silicon nanoparticles are synthesized by the pulsed plasma in liquid and the obtained silicon samples were used as additives in soil to combat plant growth, as well as against various physical factors.

2. Experimental Procedure

Reagents: silicon crystals (purity 99.999%), ethanol (96%), distilled water, potassium permanganate, soil.

A pulse generator can reduce the pulse duration of the current to 10 µs, increase the pulse amplitude (amplitude) to 100 amperes and in the resulting plasma medium, the temperature can reach up to several thousand Kelvin. However, since the length of this pulse is very small, it does not have much effect on the surrounding media, because of which there is practically no difference between the liquid temperature and the room temperature. During synthesis, water or alcohol is selected as the liquid medium. Both the anode and the cathode are connected to a silicon ingot as an electrode and anode electrode (or cathode, does not matter) was kept vibrating in order to maintain a very small gap between the electrodes throughout the experiment. After several hours of pulsed plasma operation, the resulting particles in the suspension were separated from the liquid and dried for analysis. The phase composition of the samples were determined by the X-Ray diffraction (XRD) analysis.

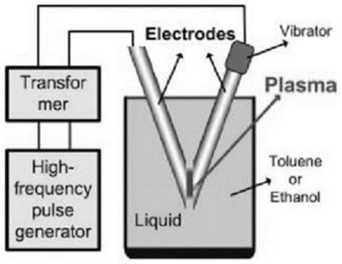

Fig. 1. Schematic representation of the pulsed plasma in liquid method.

Pure silicon ingots (cathode and anode) were fixed as shown in Figure 1. Alcohol solution of different concentrations in a glass beaker of 100 ml were used as pulsed plasma generation media. After applying the pulsed plasma several hours, the powder was filtrated from liquid and dried for analyses.

Effect of silicon nanoparticles on plants: the effect of growth height, root length, and germination percentage were studied using pulsed plasma nanoparticles as a fertilizer for barley and wheat. Wheat (Krasnodar 99) and barley (Hetman) varieties were selected and aged in 1 % potassium permanganate solution for 20 minutes to destroy pathogenic substances in the grain. Silicon nanoparticles were mixed into the soil to grow wheat and barley. The soil for growing barley and wheat was taken from pure place, where pesticides or any other treatments were not used. The soil was cleaned from various large stones, and silicon samples were mixed with the soil.

Calculation formulas for the obtained results:
a) The final percentage of germination(FGP) is calculated by the formula (Ranal and Santana 2006) as a percentage:

$$FGP = [TNGG / TNSS] *100\% \qquad (1)$$

FGP- final germination percentage,

TNGG- total number of grow grains,

TNSS- total number of seeds sown,

b) The germination rate is calculated according to the formula given below (Ksabator, 1962), as described:

$$GR=\sum(Ni/ti) \qquad (2)$$

GR- germination rate,

Ni- number of germinating grains per day,

ti- total time required for germination.

3. Results and Discussions

Figure 2 shows XRD pattern of the silicon samples taken at various concentrations. High degree of crystallization was observed in the alcohol solution of low concentration. The crystal structure of the synthesized silicon matches with the data of pure silicon structure of JCPDS card number 27-1402. Figure 3a displays a Scanning Electron Microscopy (SEM) image of the silicon samples. We can see rod shaped nanostructures. In the Figure 3b, the size distribution of the nanoparticles, measured from the SEM image was given. The average size of the silicon nanoparticles were found to be 40 nm, as shown in the graph. Nanoparticles of 20 nm and up to 100 nm in size were also observed.

Table1. Percentage of last germination, germination rate.

	Wheat				Barley			
	Control	0,005g	0,01g	0,02g	Control	0,005g	0,01g	0,02g
FGP	87,5	100	100	100	100	100	100	100
GR	1,5	1,75	1,75	2,0	1,75	1,5	2,0	1,75

In Table 1, barley and wheat were measured for 14 days from the moment of germination until the height of growth fell from the vertical position. In control wheat, the height of growth at a concentration of 0.005 g, 0.01 g was almost the same, wheat growth was higher at a concentration of 0.02 g. Control sample and barley in 0.005 g silicon soil came out within 6-8 days after planting. Barley at a concentration of 0.01 g, 0.02 g came out evenly in 4 days. The growth was higher in the amount of 0.01 grams compared to control samples of barley and other concentrations. Samples using nanoparticles showed the best results in terms of vertical position and strength. Figure 4 shows the growth of the root of barley and wheat. In barley, the nanoparticle did not have a high effect on the root. It has been observed that wheat has shorter roots as the concentration increases.

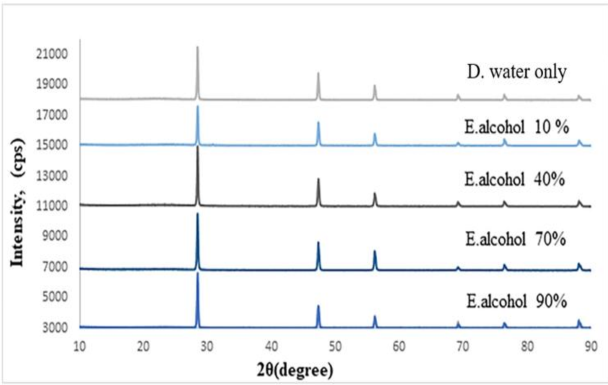

Fig. 2. XRD patterns of silicon samples, obtained by the pulsed plasma in various alcohol concebtration.

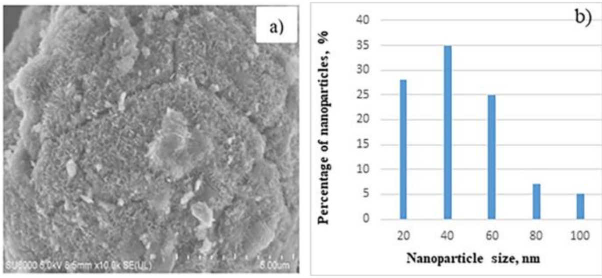

Fig. 3. a) SEM image of the silicon sample; b) the size distribution calculated from the SEM images.

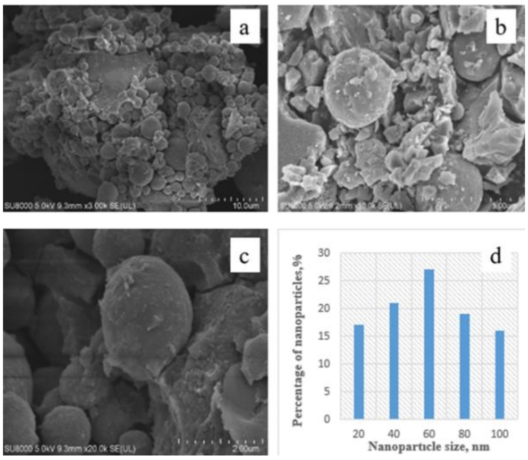

Fig. 4. SEM images of the silicon samples a), b), c); and d) size distribution of the obtained particles of 40% ethanol solution.

Figure 4 shows images of the obtained silicon samples obtained in 40 % of ethanol solution in different scales and the particle size distribution. In solution of distilled water and alcohol of 10%, 40%, 70%, 90% ratio, XRD analysis of silicon samples showed that the phase composition of all the samples is pure silicon. When analyzed using an electron microscope, it was found that the obtained silicon particles are of a spherical shape with an average size of 40 nm.

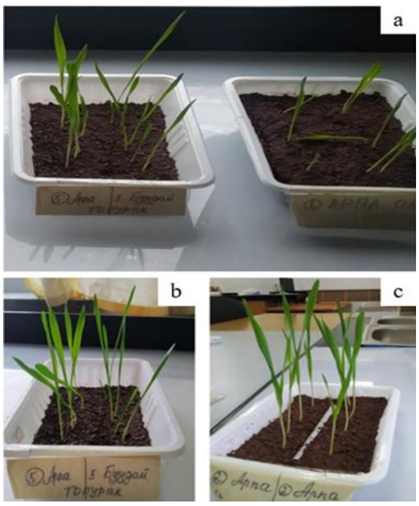

Fig. 5. a) Control sample of barley; b) barley grown in a soil with 0.5 g of silicon nanoparticles; c) barley grown in a soil with 1.0 g of silicon nanoparticles. Images were taken at the 5th day of growth.

In Figure 5. barley samples of various concentrations on the 5th day. The grains began to germinate on the 4th day after sowing, but the control barley germinated on the 6th day, the sample with a concentration of 0.005 g on the 8th day. The photo taken on the 5th day after germination, the time before germination was not added because the measurement of the height of germination was started after germination.

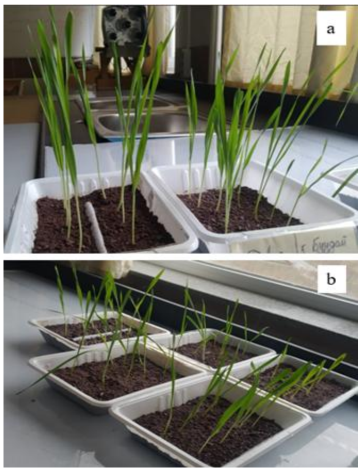

Fig. 6. Image of barley and wheat on the day 11.

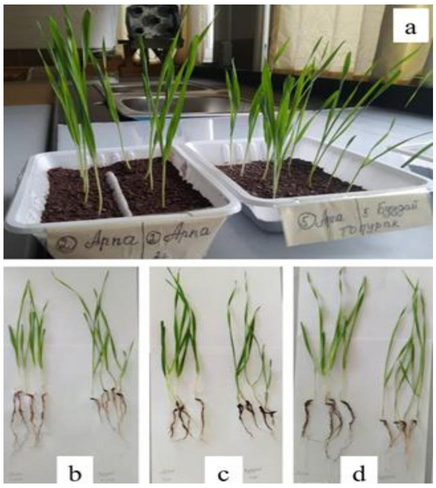

Fig. 7. Barley and wheat (a) after 9th day, (b), (c), (d) barley wheat root after 14 days

Figure 6. shows the germination of barley and wheat within 11 days. In Figure 7. germination of wheat and barley on the 9th day. The ninth day of the germination process of wheat and barley, the straight position after 14 days shows that they are b, c, d wheat and barley roots.

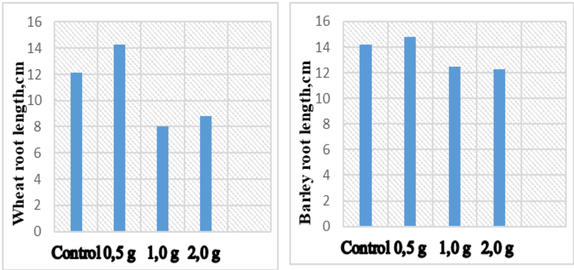

Fig. 8. The length of the root of barley and wheat control samples and silicon nanoparticles of 0.5g, 1.0g, 2.0g concentrations.

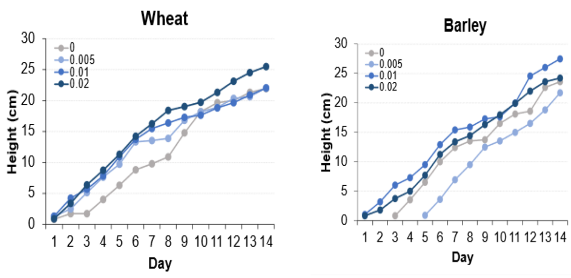

Fig. 9. Growth of wheat and barley grown for 14 days.

Figure 8 shows length of the root of barley and wheat, in Figure 9. the germination height of wheat and barley within 14 days. It seems that wheat and barley have higher germination at a concentration of 0.02g of 0.01 nanoparticles compared to other concentrations. We used silicon nanoparticles as fertilizers for wheat and barley, and for some other crops such as cucumbers and tomatoes. One of the most important effects of the silicon nanoparticles was that the samples in which silicon was used germinated earlier compared to the control sample, and the growth differed from the control sample in terms of strength of standing in upright position.

4. Conclusion

Silicon nanoparticles were synthesized from high-purity silicon ingots using the pulsed plasma method. The synthesized powder was found to contain 98% pure silicon nanoparticles. X-ray phase analysis of silicon samples obtained from distilled water and alcohol solutions with 10%, 40%, 70%, and 90% concentrations showed that the phase composition of the silicon samples consisted of pure silicon. Upon analysis with an electron microscope, the particle sizes of the obtained silicon samples were measured using the 'ImageJ contact angle plugin' software, and full data is presented in the tables above. The structural forms of the particles were identified as rod, spherical, and cubic.

The potential use of these silicon nanoparticles synthesized by the pulsed plasma method was explored in the agricultural sector. Barley and wheat grains were selected as model crops for this pilot study. These grains were ideal for laboratory conditions due to their short growth period and minimal sunlight requirements. The germination rate, growth height, and root length of the studied grain crops were compared with a control sample. Significant differences were observed in the germination rates, growth heights, and root lengths of the samples. Barley exhibited a higher germination rate and greater growth height. As the concentration of silicon nanoparticles in the soil increased, both barley and wheat developed shorter but stronger and more upright roots compared to the control.

The study concluded that using silicon nanoparticles in soil could help plants resist external stress factors. One of the main advantages of silicon nanoparticles in agriculture is their small particle size [23]. Figure 13 presents the X-ray diffractogram of silicon samples synthesized at different concentrations. As shown in the graph, the particle intensity was highest in distilled water and 40% alcohol solutions. High intensity indicated a higher degree of crystallinity. No high crystallization was observed at lower alcohol concentrations. The synthesized silicon nanoparticles matched the crystallographic data of pure silicon with JCPDS card No. 27-1402.

Table 1 shows the growth height of barley and wheat within 14 days after germination until they lost their upright position. In the control wheat and at 0.005 g and 0.01 g concentrations, growth height was nearly the same, while at 0.02 g concentration, wheat growth was higher. Control barley and barley samples at 0.005 g concentration germinated within 6 to 8 days. At 0.01 g and 0.02 g concentrations, barley germinated in 4 days. Among the barley samples, the highest growth was observed at 0.01 g of nanoparticles. In terms of upright position and strength, the nanoparticle-treated samples showed the best performance. Figure 18 presents the root development of barley and wheat. In barley, the nanoparticles had minimal effect on root length. In wheat, increased concentration resulted in shorter roots.

Silicon nanoparticles can be applied in several ways. One method involves mixing them with water and spraying for irrigation; however, the most effective impact was observed when applied directly to the soil. While other studies used spraying methods, they did not report high effectiveness; however, both abiotic and biotic resistance was observed to be stable. When used as soil, plant growth was improved, and the plants remained firm and upright. Therefore, silicon nanoparticles can be considered suitable for use on grain crops in agriculture.

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