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Effects of Nanoscale Silica Particles on Nitrogen, Phosphorus, and Potassium Content and Uptake in Rice

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Silica nanoparticles (SiNPs) are being examined as foliar inputs because silicon can influence plant growth, stress responses, and nutrient acquisition. This pot experiment evaluated the effects of foliar-applied SiNPs on nitrogen (N), phosphorus (P), and potassium (K) content and uptake in rice. The NLR 34449 rice variety was grown during the 2021 *kharif* season under ten treatments comprising a distilled-water control, the recommended dose of fertiliser (RDF), RDF with silicic acid at 4 mL L^{-1}, and RDF with SiNPs at 50, 100, 200, 400, 600, 800, or 1000 ppm. Foliar treatments were applied at 25 and 50 days after transplanting. Nutrient content and uptake were determined in straw and grain at harvest. The treatment comprising RDF

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with SiNPs at 200 ppm (T6) recorded the highest N, P, and K contents and uptake. In straw and grain, respectively, T6 recorded N contents of 0.62% and 1.36%, P contents of 0.16% and 0.34%, and K contents of 1.39% and 1.30%. Corresponding uptake values were 189.51 and 306.60 mg pot^{-1} for N, 49.62 and 76.70 mg pot^{-1} for P, and 424.72 and 293.41 mg pot^{-1} for K. Under the conditions of this pot experiment, foliar application of SiNPs at 200 ppm with RDF was associated with improved macronutrient content and uptake in rice.

Keywords: Nanoscale silica; nitrogen; phosphorus; potassium; nutrient content; nutrient uptake.

1. Introduction

Silicon (Si) is the second most abundant element, after oxygen, in the Earth's crust and occurs in most soils, mainly as various silicate minerals (Sommer et al., 2006). The concentration of the plant-available form of Si in soil solution, monosilicic acid (H_4SiO_4), ranges from 0.1 to 0.6 mM, approximately two orders of magnitude greater than phosphorus (P) concentrations (Yan et al., 2018). Silicon is lost from soil through leaching, particularly in subtropical and tropical regions, where plant-available Si is generally low; therefore, Si fertilisation can benefit these soils. Some regions have limited Si availability, which may affect sustainable crop production. Proper Si management is necessary in both temperate and tropical regions to increase yield and sustain crop productivity. Additionally, intensive cultivation and continuous monocropping of high-yielding cultivars can reduce soil Si levels. Given the growing world population and intensification of agriculture, silica supplementation may be required to maintain plant growth and yield (El-Ramady et al., 2018). In recent years, nanoscale materials, defined as materials measuring less than 100 nm in at least one dimension, have received considerable attention in agriculture. Silica nanoparticles (SiNPs), owing to their increased surface-area-to-volume ratio and quantum confinement, have become materials of interest across scientific disciplines. Sadowska and Świderski (2020) demonstrated that these nanoparticles have a high surface area, solubility, and surface reactivity, together with a small size and ease of interaction with plants. They can penetrate biological systems, including plants, more efficiently than bulk forms of silica (Rajiv et al., 2020). One notable benefit is the formation of a silicic acid layer, which helps reduce plant transpiration and enhances resistance to drought, temperature fluctuations, and humidity (Felisberto et al., 2021). This makes silica nanoparticles a promising tool in agricultural practice, with the potential to mitigate environmental stressors and improve crop resilience.

However, limited information is available on the concentration-dependent effects of foliar-applied nanoscale silica on nitrogen, phosphorus, and potassium content and uptake in rice under pot-culture conditions. Therefore, the present study aimed to evaluate the effects of foliar-applied nanoscale silica and silicic acid, in combination with the recommended dose of fertiliser, on nitrogen, phosphorus, and potassium content and uptake in rice at harvest.

2. Materials and Methods

A pot experiment was conducted at S. V. Agricultural College, Acharya N. G. Ranga Agricultural University, Andhra Pradesh, during the *kharif* season of 2021. The NLR 34449 rice variety was used to investigate the foliar effects of nanoscale silica on nitrogen, phosphorus, and potassium content and uptake at harvest. A randomised complete block design with three replications was used. Pots measuring 25 × 25 cm were filled with 10 kg of soil, and three seedlings were transplanted into each pot. The treatments were as follows: T1, control (distilled-water spray); T2, RDF (120–60–40 kg N, P_2O_5, and K_2O ha^{-1}); T3, RDF + silicic acid at 4 mL L^{-1}; T4, RDF + SiNPs at 50 ppm; T5, RDF + SiNPs at 100 ppm; T6, RDF + SiNPs at 200 ppm; T7, RDF + SiNPs at 400 ppm; T8, RDF + SiNPs at 600 ppm; T9, RDF + SiNPs at 800 ppm; and T10, RDF + SiNPs at 1000 ppm. Foliar applications of nanoscale and bulk silica were made twice, at 25 and 50 days after transplanting (DAT). Nitrogen, phosphorus, and potassium fertilisers were applied at rates of 120, 60, and 40 kg ha^{-1}, respectively. The entire phosphorus dose, as single superphosphate, and potassium dose, as muriate of potash, were applied before transplanting. Nitrogen, as urea, was applied in three splits: 40% at transplanting, 40% at 30 DAT, and the remaining 20% at 60 DAT.

2.1 Determination of Nitrogen in Plant Sample

The nitrogen content of plant samples was estimated using the micro-Kjeldahl distillation method described by Piper (1966).

2.2 Determination of Phosphorus Content in Plant Sample

Phosphorus in the di-acid extract of plant samples was estimated using the vanadomolybdophosphoric yellow-colour method with a spectrophotometer at a wavelength of 420 nm, as described by Jackson (1973).

2.3 Determination of Potassium in Plant Sample

Potassium in the di-acid extract of plant samples was determined using a flame photometer, following Jackson (1973).

2.4 Nutrient Uptake

Nutrient uptake at harvest in both straw and grain was calculated using the following formula. Macronutrient uptake was expressed as kg ha^{-1}.

$$\text{Nutrient Uptake (kg ha}^{-1}\text{)} = (\text{Nutrient content (\%) X dry matter production (kg ha}^{-1}\text{)})/\ 100$$

3. Results and Discussion

3.1 Nitrogen Content

The highest nitrogen contents in straw and grain (0.62% and 1.36%, respectively) were observed with RDF + SiNPs at 200 ppm (T6) (Table 1). These values were significantly higher than those obtained with RDF + SiNPs at 100 ppm (T5; 0.54% and 1.25%), RDF + silicic acid at 4 mL L^{-1} (T3; 0.53% and 1.24%), and RDF + SiNPs at 50 ppm (T4; 0.50% and 1.19%). The values recorded with RDF + SiNPs at 400 ppm (T7; 0.61% and 1.34%), 600 ppm (T8; 0.60% and 1.33%), 800 ppm (T9; 0.59% and 1.32%), and 1000 ppm (T10; 0.59% and 1.31%) were statistically on par with T6. The lowest nitrogen contents were observed with RDF alone (T2; 0.49% and 1.18%) and the control (T1; 0.37% and 1.08%).

Silicon application significantly increased nitrogen content; similar results were reported by Babu Rao et al. (2018). Frazão et al. (2020) reported beneficial effects of partially replacing carbon with silicon following soil application of silicon to sugarcane. This replacement reduced plant carbon concentration and was associated with greater biomass production, higher rates of nitrogen and phosphorus uptake and accumulation, and enhanced photosynthetic rates. Silicon fertilisation also improved nitrogen-use efficiency and agronomic parameters, including yield and nutritional value, in long-term rice experiments (Cuong et al., 2017).

3.2 Phosphorus Content

The highest phosphorus contents in rice straw and grain at harvest (0.16% and 0.34%, respectively) were recorded with foliar application of SiNPs at 200 ppm along with RDF (T6) (Table 1). T6 was significantly superior to RDF + SiNPs at 100 ppm (T5), RDF + silicic acid at 4 mL L^{-1} (T3), and RDF + SiNPs at 50 ppm (T4). The T6 treatment was statistically on par with RDF + SiNPs at 400 ppm (T7), 600 ppm (T8), 800 ppm (T9), and 1000 ppm (T10). The lowest phosphorus contents were recorded with RDF alone (T2; 0.11% and 0.25% in straw and grain, respectively) and the control (T1; 0.09% and 0.21%, respectively). The next-best treatment was RDF + SiNPs at 400 ppm (T7).

Phosphorus concentration increased significantly following silicon application, possibly because silicon promoted root growth and development. A well-developed root system can explore a larger soil volume, increasing the likelihood of encountering phosphorus-rich zones and thereby enhancing phosphorus uptake. Evidence suggests that silicon plays a significant role in phosphorus nutrition, although the precise nature of this role remains unclear. An alleviating effect of silicon under phosphorus-limiting conditions has been reported in wheat (Neu et al., 2017) and rice (Hu et al., 2018).

3.3 Potassium Content

Potassium content in rice straw and grain followed a trend similar to those of nitrogen and phosphorus (Table 1). The application of RDF with two foliar sprays of SiNPs at 200 ppm (T6) recorded significantly higher potassium contents in straw and grain at harvest (1.39% and 1.30%, respectively) than T5 (RDF + SiNPs at 100 ppm), T3 (RDF + silicic acid at 4 mL L^{-1}), and T4 (RDF + SiNPs at 50 ppm). The values for T6 were statistically on par with RDF + SiNPs at 400 ppm (T7), 600 ppm (T8), 800 ppm (T9), and 1000 ppm (T10). The lowest potassium contents were recorded with RDF (T2; 1.23% and 1.13% in straw and grain, respectively) and the control (T1; 0.93% and 0.89%, respectively).

Silicon application significantly increased potassium concentration. These results agree with those of Pati et al. (2016), who attributed the increase in potassium concentration to cell-wall silicification. Patil et al. (2018) reported that the increase in potassium concentration might also be associated with the stimulatory effect of silicon on H^+-ATPase activation in the membrane.

3.4 Nitrogen Uptake

The highest nitrogen uptake in straw and grain at harvest (189.51 and 306.60 mg pot^{-1}, respectively) was recorded with T6 (SiNPs at 200 ppm along with RDF), which was significantly higher than all other treatments (Table 2 and Fig. 1). The next-best treatments were T7 (182.31 and 293.06 mg pot^{-1} in straw and grain, respectively), T8 (175.81 and 287.63 mg pot^{-1}, respectively), T9 (171.21 and 280.83 mg pot^{-1}, respectively), and T10 (166.80 and 274.89 mg pot^{-1}, respectively). The lowest nitrogen uptake was recorded with RDF (T2; 103.49 and 162.81 mg pot^{-1} in straw and grain, respectively) and the control (T1; 43.55 and 66.42 mg pot^{-1}, respectively). Compared with RDF + silicic acid at 4 mL L^{-1} (T3; 136.23 and 218.44 mg pot^{-1}), T6 increased nitrogen uptake by 39.11% in straw and 40.36% in grain.

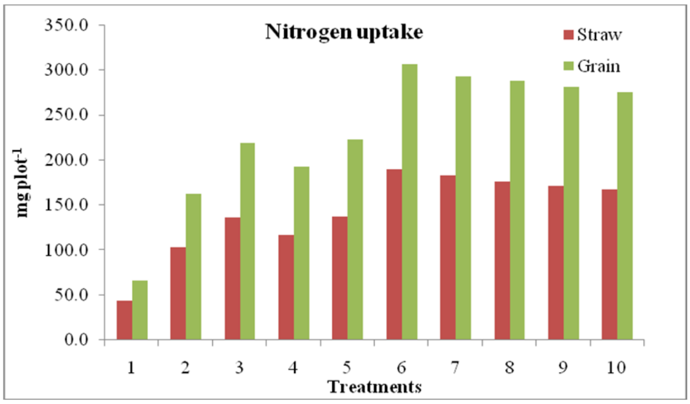

Fig. 1. Effect of different concentrations of nanoparticulate silica on nitrogen uptake of rice in pot culture experiment

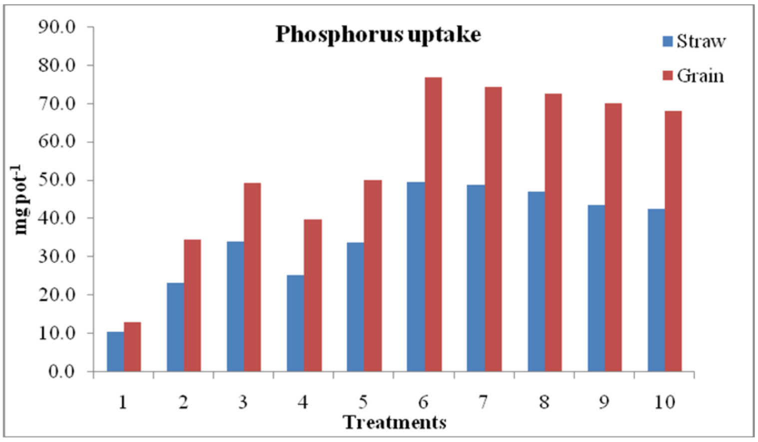

Fig. 2. Effect of different concentrations of nanoparticulate silica on phosphorus uptake of rice in pot culture experiment

Table 1. Effect of different concentrations of nanoparticulate silica on N, P and K content of rice in pot culture experiment

Treatments	Nitrogen (%)		Phosphorus (%)		Potassium (%)	
	Straw	Grain	Straw	Grain	Straw	Grain
T_1-Distilled water spray)	0.37	1.08	0.09	0.21	0.93	0.89
T_2-RDF	0.49	1.18	0.11	0.25	1.23	1.13
T_3-T_2+ Foliar application of silicic acid @ 4 ml l^{-1}	0.53	1.24	0.13	0.28	1.28	1.18
T_4 -T_2+ Foliar application of nanoscale silica @ 50 ppm	0.50	1.19	0.11	0.25	1.25	1.14
T_5 -T_2+ Foliar application of nanoscale silica @ 100 ppm	0.54	1.25	0.13	0.28	1.28	1.18
T_6 -T_2+ Foliar application of nanoscale silica @ 200 ppm	0.62	1.36	0.16	0.34	1.39	1.30
T_7 -T_2+ Foliar application of nanoscale silica @ 400 ppm	0.61	1.34	0.16	0.34	1.37	1.28
T_8 -T_2+ Foliar application of nanoscale silica @ 600 ppm	0.60	1.33	0.16	0.34	1.36	1.26
T_9 -T_2+ Foliar application of nanoscale silica @ 800 ppm	0.59	1.32	0.15	0.33	1.36	1.26
T_{10}-T_2+ Foliar application of nanoscale silica @ 1000 ppm	0.59	1.31	0.15	0.32	1.35	1.25
S.Em±	0.01	0.02	0.004	0.006	0.01	0.02
CD (0.05)	0.03	0.05	0.01	0.02	0.04	0.06

Table 2. Effect of different concentrations of nanoparticulate silica on n, p and k uptake of rice in pot culture experiment

Treatments	Nitrogen (mg pot^{-1})		Phosphorus (mg pot^{-1})		Potassium (mg pot^{-1})	
	Straw	Grain	Straw	Grain	Straw	Grain
T_1-Distilled water spray)	43.55	66.42	10.59	12.92	109.46	54.77
T_2-RDF	103.49	162.81	23.23	34.38	259.93	154.89
T_3-T_2+ Foliar application of silicic acid @ 4 ml l^{-1}	136.23	218.44	33.91	49.27	327.30	207.95
T_4 -T_2+ Foliar application of nanoscale silica @ 50 ppm	116.20	192.02	25.15	39.77	290.13	184.05
T_5 -T_2+ Foliar application of nanoscale silica @ 100 ppm	137.29	222.17	33.75	49.95	327.19	209.94
T_6 -T_2+ Foliar application of nanoscale silica @ 200 ppm	189.51	306.60	49.62	76.70	424.72	293.41
T_7 -T_2+ Foliar application of nanoscale silica @ 400 ppm	182.31	293.06	48.82	74.36	409.46	279.94
T_8 -T_2+ Foliar application of nanoscale silica @ 600 ppm	175.81	287.63	46.88	72.38	398.88	271.70
T_9 -T_2+ Foliar application of nanoscale silica @ 800 ppm	171.21	280.83	43.53	69.91	393.58	267.29
T_{10}-T_2+ Foliar application of nanoscale silica @ 1000 ppm	166.80	274.89	42.41	67.99	382.84	261.25
S.Em±	2.06	3.27	0.66	0.99	4.42	4.37
CD (0.05)	6.07	9.64	1.93	2.91	13.05	12.90

Silicon promotes the development of a healthy and well-branched root system. This improved root architecture increases the surface area available for nutrient absorption, including nitrogen (Tripathi et al., 2021). Consequently, silicon-treated plants may have a greater capacity to acquire nitrogen from the soil. Pati et al. (2016) reported that nitrogen uptake increased significantly following silicon application, possibly because silicon can increase soil-available nitrogen and nitrogen-use efficiency. Silicon also has a synergistic effect with nitrogen and therefore enhances nitrogen uptake (Patil et al., 2018).

3.5 Phosphorus Uptake

At harvest, T6 (SiNPs at 200 ppm along with RDF) recorded the highest phosphorus uptake in straw and grain (49.62 and 76.70 mg pot^{-1}, respectively) and was statistically on par with T7 (RDF + SiNPs at 400 ppm; 48.82 and 74.36 mg pot^{-1}, respectively) (Table 2 and Fig. 2). T6 recorded significantly greater phosphorus uptake than T8 (RDF + SiNPs at 600 ppm), T9 (RDF + SiNPs at 800 ppm), T10 (RDF + SiNPs at 1000 ppm), T5 (RDF + SiNPs at 100 ppm), T3 (RDF + silicic acid at 4 mL L^{-1}), and T4 (RDF + SiNPs at 50 ppm). The minimum phosphorus uptake was observed with RDF alone (T2) and the control (T1).

Silicon application significantly increased phosphorus uptake; similar results were reported by Babu Rao et al. (2018). Silicon-induced increases in the expression of genes associated with inorganic phosphorus (Pi) uptake have been observed in wheat (Kostic et al., 2017). Hellal et al. (2012) observed that a 0.4% foliar spray of silicon as diatomite, together with farmyard manure (FYM), recorded maximum phosphorus uptake of 18.38 kg fed^{-1} in grain and 9.39 kg fed^{-1} in straw.

3.6 Potassium Uptake

The highest potassium uptake in straw and grain at harvest (424.72 and 293.41 mg pot^{-1}, respectively) was recorded with T6 (SiNPs at 200 ppm along with RDF), which was significantly higher than all other treatments (Table 2 and Fig. 3). The next-best treatments were T7 (409.46 and 279.94 mg pot^{-1} in straw and grain, respectively), T8 (398.88 and 271.70 mg pot^{-1}, respectively), T9 (393.58 and 267.29 mg pot^{-1}, respectively), and T10 (382.84 and 261.25 mg pot^{-1}, respectively). The lowest potassium uptake was recorded with RDF (T2; 259.93 and 154.89 mg pot^{-1} in straw and grain, respectively) and the control (T1; 109.46 and 54.77 mg pot^{-1}, respectively). Compared with RDF + silicic acid at 4 mL L^{-1} (T3; 327.30 and 207.95 mg pot^{-1}), T6 increased potassium uptake by 29.76% in straw and 41.10% in grain. Increased potassium uptake by silicon-supplied rice plants grown under saline conditions may result from silicon-mediated stimulation of H^+-ATPase activity (Liang et al., 2003) or upregulation of K^+ transporter genes (OsHAK1, OsAKT1, and OsSKOR) by silicon (Yan et al., 2021).

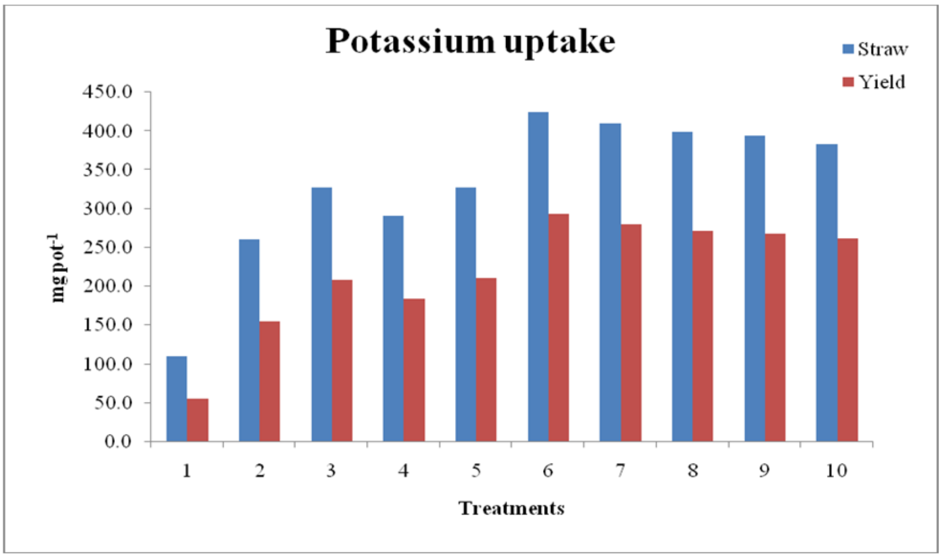

Fig. 3. Effect of different concentrations of nanoparticulate silica on potassium uptake of rice in pot culture experiment

4. Conclusion

The pot experiment showed that the response of rice nutrient status to foliar-applied nanoscale silica varied with concentration. Across the evaluated treatments, the combination of the recommended dose of fertiliser with SiNPs at 200 ppm (T6) consistently recorded the highest nitrogen, phosphorus, and potassium contents and uptake in both straw and grain at harvest. Nutrient responses at concentrations above 200 ppm were generally statistically comparable or lower, indicating that increasing the SiNP concentration beyond 200 ppm did not provide a corresponding improvement under the experimental conditions. The results therefore identify 200 ppm SiNPs with RDF as the most effective treatment among those tested for improving macronutrient content and uptake. Nevertheless, the findings are confined to the NLR 34449 rice variety grown in a pot experiment during one *kharif* season. Accordingly, the treatment should be interpreted as promising within the tested conditions rather than as a general recommendation for field production. Validation under field conditions and across different soils, seasons, and rice varieties is necessary before wider agronomic application.

5. Limitations

This study was conducted as a single-season pot experiment using one rice variety and three replications. The findings therefore reflect controlled pot-culture conditions and may not represent responses under diverse field soils, climates, or management systems. The study assessed nitrogen, phosphorus, and potassium content and uptake at harvest but did not examine long-term soil effects, silicon accumulation, physiological mechanisms, environmental fate, or economic feasibility.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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