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Silicon Sources and Bacterial Inoculants on Growth Parameters, Leaf Yield, Quality of Coriander (*Coriandrum sativum* L.) and Soil Adsorbed Silicon in Sandy Loam Soil

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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

Aims: The objective of the present study was to investigate the effect of different silicon sources with and without microbial inoculants on growth parameters, leaf yield and quality of Coriander.
Study Design: Factorial Completely Randomized Block Design (FCRD) was used in the present study with thirty-six treatments and three replications.
Place and Duration of Study: The pot culture experiment was carried out in the Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore, India during January to March 2022.
Methodology: A pot culture experiment was conducted with different silicon sources namely $CaSiO_3$, $MgSiO_3$ and Rice Husk Ash (RHA) at three levels (0, 50 and 100 mg Si kg^{-1}) with and without two silicate solubilizing bacteria (SSB) and a zinc solubilizing bacterium (ZSB) at 2 kg ha^{-1} with coriander CO (CR) 4. The influence of the treatments on growth parameters, leaf Si content,

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leaf yield, total soluble sugar content of leaf and soil adsorbed Si were investigated at 25 and 50 DAS.
Results: The results revealed a significant influence of Si sources with bacterial inoculants. The plant height and SPAD index values were the highest by the application of RHA @ 100 mg Si kg^{-1} + SSB4 followed by $CaSiO_3$ @ 100 mg Si kg^{-1} + SSB4. All the sources increased the leaf Si as well as soil adsorbed Si and the effect was highly significant when Si sources were combined with SSB4 and other inoculants. Coriander leaf yield ranged from 4.32 to 8.24 g plant^{-1}. The maximum leaf yield was recorded with the application of RHA @ 100 mg Si kg^{-1} with SSB4 (8.24 g plant^{-1}) followed by RHA @ 50 mg Si kg^{-1} with SSB4 (7.67 g plant^{-1}) and $CaSiO_3$ @ 100 mg Si kg^{-1} with SSB4 (7.56 g plant^{-1}). The effect of Si sources with bacterial inoculants on TSS content of leaf was significant with a maximum value of (38.23 mg g^{-1} DW) by RHA @ 100 mg Si kg^{-1} + SSB4 followed by $CaSiO_3$ @ 100 mg Si kg^{-1} + SSB4 (36.10 mg g^{-1} DW).
Conclusion: The current study revealed that the combined application of Si sources and microbial inoculants significantly enhanced the growth attributes, leaf Si, leaf yield, leaf quality of coriander and soil adsorbed Si. The leaf yield increase over control for RHA @ 100 mg Si kg^{-1} with SSB4 was 88.92 per cent followed by RHA @ 50 mg Si kg^{-1} with SSB4 (76.58%) and $CaSiO_3$ @ 100 mg Si kg^{-1} with SSB4 (73.82%). The research work needs further validation at the field level.

Keywords: Silicon sources; leaf yield; Si content; coriander; Bacillus altitudinis; Pseudomonas gessardii; Bacillus aryabhattai.

1. INTRODUCTION

Silicon (Si) is the second most abundant element in the earth's crust after oxygen. The uptake of other nutrients by plants is positively impacted by Si. Due to its strong affinity for oxygen, silicon typically appears in nature as silica (SiO_2) [1]. Depending on the pH of the soil, it can also be found as silicic acid [H_4SiO_4] and silicate [2]. However, the capacity of different plant species to accumulate silicon varies substantially, with values ranging from 0.1 percent to 10 percent silicon on a dry weight basis [2]. Si moves from the root to the shoot area after being absorbed by the soil, where it can trigger a variety of physiological responses, such as crop improvement and growth, enzymatic activities and expression of genes. Si is able to regulate the availability of several elements in soils by competing with silicic acid for binding on soil particles [3].

Si increases the rate of photosynthesis, which is affected by the ultrastructure of the leaf, the level of chlorophyll, and the activity of the enzyme ribulose bisphosphate carboxylase. In addition to making plant cell walls thicker and more durable, silicon also expands the vascular system [4]. The increased vascular system allows for greater water and nutrient uptake, strengthening the plant in all ways. Si spraying dramatically increased relative water content (RWC) by promoting plant development, enhancing the capacity of roots to absorb more water from the growth medium, and enhancing water flow from roots to leaves. It also modulates plant water potential, stomatal conductance, and transpiration rate. By causing a number of transcriptional changes, Si plays a significant part in the creation of elicitor-accelerated secondary metabolites [5]. The silicate minerals that are formed during weathering and are dissolved in the soil solution are affected by diffusion and leaching.

Coriander (*Coriandrum sativum* L.), is one of the India's major spice crops, known as Dhania, Cilantro, Chinese parsley, Mexican parsley, and Japanese parsley [6], a member of the family *Apiaceae* or *Umbelliferae*. It is widely used in the food, beverage, pharmaceutical, cosmetic, and sanitary industries. It is a culinary and medicinal plant that originated in southern Europe and the Mediterranean region. Coriander is grown all year long in India for both tender leaves and grains. The best time to grow coriander is during the rabi season. Although any type of soil, including light, well-drained, moist, loamy, and light to heavy black soil, can support its growth, dry climates are best for it. In India, this crop is cultivated in an area of 2,94,542 ha with an estimated yield of 11,01,920 metric tonnes in 2021 [7]. On a bigger scale, it is grown in Rajasthan, Madhya Pradesh, Tamil Nadu, Gujarat, Karnataka, Maharashtra, Orissa, and Andhra Pradesh. The aroma of the coriander fruit is significantly different from that of the herb, which is due to changes in essential oil and its chemical composition throughout ontogenesis. Its green leaf, which is rich in fiber, carbohydrates, proteins, vitamins, and minerals (including calcium, phosphorus, and iron), is used as a vegetable and in salads as well as in cooking as an ingredient in many foods. Indigestion, dyspepsia, flatulence, and piles can all be treated with the seeds and leaves of this plant [8].

Numerous studies have demonstrated that using bio-fertilizers instead of synthetic fertilizers can increase crop yields and plant growth while using less dangerous agrochemicals. Based on specific strains of the genus *Bacillus* that have been proven to have natural benefits. These bacteria provide the ability to plants to withstand biotic and abiotic stress by solubilizing silicon. In addition to the insoluble forms of silicon, silicate-solubilizing bacteria (SSB) may also solubilize potassium and phosphate which helps in increasing soil fertility and crop yield. Zinc Solubilizing Bacteria (ZSB) also act as plant growth-promoting factors which produce Indole acetic acid (IAA) and due to this it may have an impact on the growth of various plant species [9]. According to Narayanaswamy and Prakash [10], paddy plants cultivated on Inceptisol soils eliminated a total of 205 to 611 kg/ha of Si. Si may become a yield-limiting component for rice cultivation; hence the use of exogenous Si fertilizer may be required for a system of rice production that is both profitable and sustainable. The research on Silicon sources with SSB on Coriander in respect of leaf yield and quality is very meagre. Hence this study was carried out to investigate the effect of different silicon sources with and without microbial inoculants on growth parameters, leaf yield, and quality of Coriander.

2. MATERIALS AND METHODS

2.1 Pot Culture Experiment

A pot culture experiment was conducted at the Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore during January to March 2022. The bulk soil sample low in adsorbed silicon collected from Madukkarai, Coimbatore (Latitude: 10°53’33.6”N and Longitude: 76°56’36.1”E) was processed and each pot was filled with ten kg of soil. The soil was alkaline in soil reaction with an EC of 0.27 dS m^{-1}, low organic carbon (0.32%) and low organic matter (0.55%). The available nitrogen (183.86 kg ha^{-1}) was low whereas available phosphorus (15.51 kg ha^{-1}) and available potassium (222 kg ha^{-1}) were medium in status. The adsorbed silicon (0.5 M acetic acid method) of experimental soil was low (11.49 mg Kg^{-1}). Soils were treated with three different silicon sources *viz*., calcium silicate ($CaSiO_3$), magnesium Silicate ($MgSiO_3$), and Rice Husk Ash (RHA) with three levels (0, 50 and 100 mg Si kg^{-1}). Lignite based bio-inouclants *viz*., two Silicate Solubilizing Bacteria (*Bacillus altitudinis* SSB4 & *Pseudomonas gessardii* SSB7) and one Zinc Solubilizing Bacteria (ZSB) (*Bacillus aryabhattai* $KSBN_2K_7$) obtained from the Department of Agricultural Microbiology, Tamil Nadu Agricultural University, Coimbatore and applied to the soil at 2 kg ha^{-1}. 10 kgs of soil was filled in each pot (top diameter, 28.0 cm; base diameter, 24.0 cm and height, 22.5 cm).

Coriander CO (CR) 4 seeds that were obtained from the Department of Spices and Plantation Crops, Tamil Nadu Agricultural University, Coimbatore, were split in half, immersed in water overnight, and then treated with *Trichoderma viridi* before sowing. 15 seeds were sown in each pot and 25 days after sowing 10 plants per pot were retained. Seeds were sown at 1 cm depth and sufficient irrigation was applied to pots till the last stage. Throughout the growing season, standard management practices were followed as per Crop Production Guide, 2020, TNAU. After two weeks of germination, they were reduced to ten plants per pot. The plant samples were collected at two stages *viz*., 25 DAS and 50 DAS (Days after Sowing) and analyzed for various parameters by adopting standard procedures. The study was laid out in a Factorial Completely Randomized Block Design (FCRD) consisting of thirty-six treatments and replicated thrice.

2.2 Plant Height (cm)

Plant height was measured using a scale from the base of the plant to the tip at two stages *viz.*, 25 DAS & 50 DAS. The plant height was calculated using the average of five plants in every pot and expressed in centimeters (cm).

2.3 Leaf SPAD Index Value

Leaf SPAD (Soil and Plant Analysis Development; an indication of leaf greenness) values were measured in the second expanded leaves from the top at two cropping stages (25 DAS & 50 DAS) using a portable SPAD-502 Chlorophyll Meter (Minolta Camera Co. Ltd., Tokyo, Japan). The average leaf SPAD value was calculated from 10 readings of plant leaves per pot.

2.4 Coriander Leaf Yield (g/plant)

The plants were chosen randomly from each treatment, and the fresh weight of the herbage was measured by removing any adherent soil from the roots and expressed as grams per plant.

2.5 Estimation of Leaf Silicon

To analyze plant Si, dry powdered coriander leaf samples (0.1 g) were digested in a mixture of 70% HNO_3 (7 ml), 30% H_2O_2 (2 ml), and 40% Hydrofluoric acid (HF) (1 ml) with the help of a microwave digestion system (Anton Paar-Multiwave PRO) with following steps: 1200 watts for 20 minutes with a ramping rate of 7°C per minute and 1200 watts for 30 min at holding temperature of 170°C and venting for 20 min. The digested samples were diluted with 4% boric acid and made up the volume of 50 ml [10]. The Si content of digested samples was determined by the standard Spectro-photometry method as described by Ma et al. [11].

2.6 Estimation of Adsorbed Silicon (Ad-Si) in Soils

Adsorbed silicon (Ad-Si) in soils was estimated using the 0.5 M acetic acid method. 5 gm soil was added into a 50 ml plastic centrifuge tube then 12.5 ml of 0.5 M acetic acid was added [12]. After shaking in an end-over-end shaker continuously for one hour, centrifuged the samples at 3000 rpm for 3 minutes. The supernatant was filtered and used to measure the amount of adsorbed silicon [10]. 0.25 ml of filtrate was taken as an aliquot, and 10.5 ml of distilled water and 0.25 ml of 1:1 hydrochloric acid were added to the centrifuge tube. After allowing it to stand for 2 minutes, 0.5 ml of 10 percent ammonium molybdate solution (pH = 7.5) was added. After 5 minutes, 0.5 ml of 20 percent tartaric acid solution was added. Then two additional minutes, a 0.5 ml reducing agent (1-amino-2-naphthol-4-sulfonic acid, ANSA) was added. After 5 minutes, but no later than 30 minutes of adding the reducing agent, absorbance was measured at 630 nm using a UV/VIS spectrophotometer (LABINDIA Analytical, UV-3200 series). Si standards (0, 0.2, 0.4, 0.8, 1.2, and 1.6 mg Si L^{-1}) were prepared simultaneously and measured in a UV/VIS spectrophotometer.

Calculation:

Ad-Si (ppm or mg kg^{-1}) = (ppm obtained from standard graph x Volume of extractant x Volume made)/ (Weight of soil x Aliquot taken)

2.7 Total Soluble Sugar (TSS)

TSS was analyzed using the anthrone method as described previously [13] with glucose serving as the standard.100mg of dried coriander leaves were put into a centrifuge tube and 1.5 mL of 80% ethanol was added for homogenization. After that kept it for 30 min for incubation in a water bath at 100°C, then the mixture was cooled rapidly and centrifuged at 6000 rpm for 10 min at 4°C. The supernatant was collected and measured at 620 nm using UV/VIS spectrophotometer.

2.8 Statistical Analysis

The data for the various parameters obtained from the experiment were statistically analyzed by AGRES software version 7.01. To detect differences between treatments that were statistically significant via analysis of variance (ANOVA), Duncan's multiple range test (DMRT) were used at the 5% level of significance (P= 0.05) [14].

3. RESULTS AND DISCUSSION

The different silicon sources and microbial inoculants significantly influenced the plant growth parameters, leaf yield and quality of Coriander.

3.1 Plant Height

The plant height of coriander ranged from 8.31 to 15.98 cm at 25 DAS and 18.18 to 38.48cm at 50 DAS due to the influence of Si sources and bio-inoculants (Table 1). The treatment of rice husk ash @ 100 mg Si kg^{-1} + SSB4 recorded the maximum plant height among the prescribed treatments, whereas the control displayed the minimum plant height at 25 DAS. At 50 DAS, the maximum plant height of 38.48 cm was recorded by rice husk ash @ 100 mg Si kg^{-1} + SSB4 application while the control treatment showed a minimum value. RHA recorded the highest value of plant height among the various silicon sources, followed by calcium silicate and magnesium silicate. With a rise in silicon fertilizer levels, the plant height grew significantly. The plant height was increased by the bacterial strains in the sequence of without microbes <

ZSB < SSB7 < SSB4. The interaction effects were found to be significant at both the stages *i.e*., 25 & 50 DAS as shown in Table 1. Ahmad et al., [15] and Pati et al., [16] showed a similar increase in plant height with the addition of Si fertilizers over control and claimed that the applied silicon promotes water status and increases plant photosynthetic rate, making the crop long and firm. According to Yoshida et al., [17] the erectness of the leaves and stems, is a result of Si deposition in the cell wall, which can result in an increase in rice plant height. According to Gascho et al., [18] the stem diameter was linearly related to the rate of Si applied, whereas the height of the sugarcane crop was quadratically related. Goteti et al., [19] reported that ZSB inoculation improves the maize shoot height.

3.2 SPAD Index values

SPAD Index values increased from 21.10 to 40.31 at 25 DAS while at 50 DAS it ranged from 19.15 to 35.68 as shown in Table 2. Among the treatments, application of rice husk ash @ 100 mg Si kg^{-1} with SSB4 showed the maximum SPAD values at both stages due to silicon fertilization which might have increased the chloroplasts size and number of grana in leaves whereas the control treatment displayed a minimum value at 25 and 50 DAS. SPAD Index values increased linearly with increased levels of silicon sources. The mean SPAD value at 25 DAS increased from 24.02 to 29.62, 25.78 to 33.24, and 28.18 to 35.06 in the case of $MgSiO_3$, $CaSiO_3$, and RHA, respectively while at 50 DAS it was 20.67 to 26.91, 22.18 to 29.92 and 24.26 to 31.52. The SPAD index values at 50 DAS were lower compared to the values at 25 DAS irrespective of sources, levels of Si and bio inoculants. SSB4 showed higher SPAD Index values compared to SSB7 and ZSB, while treatments without microbes displayed lower values. Si causes an increase in growth that is accompanied by an improved rate of photosynthesis in various crops which is ultimately influenced by leaf ultrastructure, chlorophyll concentration, and ribulose bisphosphate carboxylase activity. According to Soundararajan et al., [20] Si changes the leaf posture and increases total leaf area, increasing theamountoflightthatplantscanabsorb, potentially leading to increased chlorophyll synthesis.

3.3 Coriander Leaf Si

The effect of silicon sources with bacterial inoculants on leaf silicon percentage was presented in Table 3. At 25 DAS, the leaf silicon ranged from 1.35 to 3.38 per cent, where in the applied rice husk ash @ 100 mg Si kg^{-1} + SSB4 and control displayed maximum (3.38%) and minimum (1.35%) leaf silicon percentage, respectively. The leaf silicon ranged from 2.01 per cent (control) to 4.11 per cent (Rice Husk Ash @ 100 mg Si kg^{-1} + SSB4) at 50 DAS. The mean leaf silicon at 25 DAS increased from 1.50 to 1.99, 1.59 to 2.20, and 1.76 to 3.38 per cent in the case of $MgSiO_3$, $CaSiO_3$, and RHA, respectively while at 50 DAS it was 2.19 to 2.91, 2.34 to 3.22 and 2.57 to 3.45 per cent. RHA increased plant silica content, which suggested that when it decomposes over time, more silica will be exposed because phytoliths will be freed from the plant matrix and dissolved [21]. Si content in coriander leaves might have increased because $CaSiO_3$ was more reactive and effective at supplying Si to the soil and plants than $MgSiO_3$. The leaf silicon continuously increased as silicon fertilizer levels increased. The leaf silicon was increased significantly by the bacterial strains in the sequence of without bacteria < ZSB < SSB7 < SSB4 at both stages. The results are in accordance with [22] who suggested the improvements of Si content in rice seedlings through the application of rice husk ash (RHA) and other soil organic matters. Peera et al., [23] found that the application of SSB with FYM significantly increased the silicon content in rice.

3.4 Coriander Leaf Yield

The effect of silicon sources with bacterial inoculants on the leaf yield of coriander was significant and furnished in Table 4. Different silicon sources increased the leaf yield of coriander which was in the sequence of $MgSiO_3$ < $CaSiO_3$ < RHA. The maximum coriander leaf yield was recorded with the application of rice husk ash @ 100 mg Si kg^{-1} with SSB4 (8.24 g $plant^{-1}$) followed by Rice Husk Ash @ 50 mg Si kg^{-1} with SSB4 (7.67 g $plant^{-1}$) and $CaSiO_3$ @ 100 mg Si kg^{-1} with SSB4 (7.56 g $plant^{-1}$). The effect of RHA was found to be superior compared to $CaSiO_3$ and $MgSiO_3$. However, the influence of RHA @ 50 mg Si kg^{-1} and $CaSiO_3$ @ 100 mg Si kg^{-1} were found to be comparable with each other, when the sources were combined with SSB4. With SSB7 the higher doses of RHA @ 50 and 100 mg Si kg^{-1} were at a par with each other with values of 7.39 and 7.13 g $plant^{-1}$ respectively. Among the inoculants, the mean values of leaf yield were the highest for SSB4 (6.59 g $plant^{-1}$) compared to SSB7

Table 1. Silicon Sources and bacterial Inoculants on plant height of Coriander

Plant Height (cm) at 25 DAS																
Si Sources	**No Microbes**				**SSB4**				**SSB7**				**ZSB**			
Si Levels (mg Si kg^{-1})	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**
0	8.31	8.47	8.56	8.45	11.68	11.51	11.57	11.59	10.30	9.78	10.31	10.13	9.55	9.51	9.53	9.53
50	9.91	9.36	10.58	9.95	14.89	12.29	14.68	13.95	11.24	10.36	12.23	11.27	10.44	9.82	10.69	10.32
100	11.03	10.56	12.29	11.29	15.22	13.46	15.98	14.89	13.02	11.14	13.57	12.57	11.89	10.71	12.89	11.83
Mean	9.75	9.46	10.48	9.90	13.93	12.42	14.08	13.48	11.52	10.43	12.04	11.33	10.63	10.01	11.04	10.56
Factors	**M**		**S**		**L**		**M x S**		**M x L**		**S x L**		**M x S x L**			
SEd	0.075		0.065		0.065		0.130		0.130		0.112		0.225			
LSD (*P*=0.05)	0.149		0.129		0.129		0.259		0.259		0.224		0.448			
Plant Height (cm) at 50 DAS																
Si Sources	**No Microbes**				**SSB4**				**SSB7**				**ZSB**			
Si Levels (mg Si kg^{-1})	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**
0	18.93	18.18	18.89	18.67	28.90	29.06	29.57	29.17	25.78	25.83	26.10	25.90	21.93	21.18	21.89	21.67
50	23.23	21.94	24.81	23.33	32.59	32.33	33.97	32.96	31.00	30.02	33.33	31.45	27.44	26.00	29.00	27.48
100	25.20	23.57	29.55	26.11	34.72	34.01	38.48	35.74	34.01	32.61	35.42	34.01	32.75	29.25	34.71	32.24
Mean	22.46	21.23	24.42	22.70	32.07	31.80	34.01	32.62	30.27	29.49	31.62	30.46	27.38	25.48	28.54	27.13
Factors	**M**		**S**		**L**		**M x S**		**M x L**		**S x L**		**M x S x L**			
SEd	0.17		0.147		0.147		0.295		0.295		0.255		0.511			
LSD (*P*=0.05)	0.339		0.294		0.294		0.588		0.588		0.509		1.018			

DAS – Days After Sowing; RHA – Rice Husk Ash; SSB – Silicate Solubilizing Bacteria; ZSB – Zinc Solubilizing Bacteria;
M – Microbes; S – Sources; L – Levels; Sed – Standard Error of difference; LSD – Least Significant Difference;
SSB4 – Bacillus altitudinis; SSB7 – Pseudomonas gessardii; ZSB – Bacillus aryabhattai

(5.86 g plant^{-1}) and ZSB (5.24 g plant^{-1}) irrespective of Si sources. Whereas, the mean leaf yield was 5.08 g plant^{-1} only without microbial inoculants. The results obtained by Peera et al., [23] was in corroboration with the current findings. The control without silicon sources and without bacterial inoculants showed a minimum leaf yield. As the amount of silicon fertilizer improved, the leaf yield increased with time. Pati et al., [16] noted the same result in rice crops with rising Si levels. When compared to SSB7 and ZSB, SSB4 recorded greater leaf yield per plant, whereas treatments lacking bacteria showed lower values. Due to SSB ability to dissolve insoluble types of silicates, soil fertility is increased, and plant defense mechanisms are strengthened. Afshari et al., and Hassanein et al. [24,25] observed that the application of silicon increased the leaf yield of coriander. Effect of silicon sources with and without microbes on per cent leaf yield of coriander in shown in Fig. 1.

Many studies reported that Si fertilization can increase the number of grains as well as the number of tillers per hill [16], by improving carbohydrates in a panicle. According to numerous studies, exogenous Si delivery to various horticultural crops, including cucumber, squash, bean, tomato, and roses, may lead to improved growth and productivity. Singh et al., and Ma et al., [26,27] suggested that the application of Si improved spikelets number per panicle, mature grain percentage, dry matter, and yield of rice. Application of calcium silicate as a Si source significantly increases rice and sugarcane yield over the control. Peera et al., [23] found that the application of SSB with FYM significantly increases plant growth. Rosas et al., [28] found that addition of ZSB to sandy loam soil in Argentina boosts wheat production by 36 per cent.

3.5 Adsorbed Silicon in Soil

Adsorbed silicon in soil ranged from 12.16 to 27.10 mg kg^{-1} at 25 DAS while at 50 DAS, it ranged from 17.79 to 39.63 mg kg^{-1} (Table 5). The maximum Ad-Si value was shown at both stages by the application of Rice Husk Ash @ 100 mg Si kg^{-1} with SSB4, whereas the control treatment without silicon source and without microbes displayed a minimum value. The mean Ad-Si at 25 DAS ranged from 13.22 to 19.48, 14.19 to 19.77, and 15.11 to 22.05 mg kg^{-1} while at 50 DAS it was 19.34 to 25.17, 20.51 to 28.68, and 22.41 to 32.25 mg kg^{-1} for $MgSiO_3$, $CaSiO_3$, and RHA, respectively. As the amount of silicon fertilizer increased, the Ad-Si continuously increased. The Ad-Si was raised significantly by the application of bacterial strains in the sequence of without microbes < ZSB < SSB7 < SSB4 at both stages. The interaction effects were found to be significant at both the stages *i.e.*, 25 & 50 DAS. The higher Si uptake with the use of Si fertilizer might be attributed to the increased availability of Si in the soil and the improved root system, both of which might have encouraged the plant to absorb more Si from the soil solution [16]. The application of silicon improves plant growth by increasing soil silicon content and other nutrients as well. SSB improves the rice biomass by improving the soil silicon content [29].

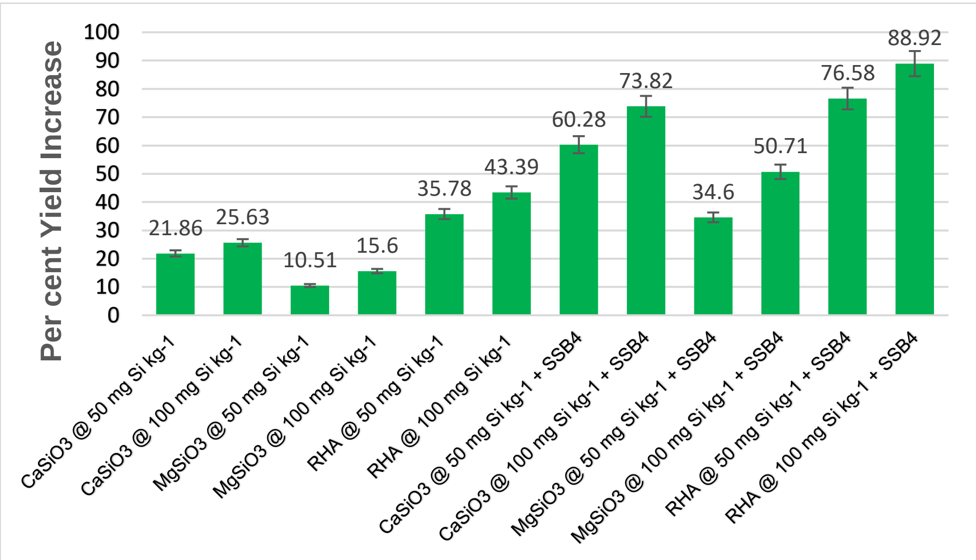

Fig. 1. Silicon sources with and without *Bacillus altitudinis* SSB4 on per cent leaf yield increase in Coriander

Table 2. Silicon Sources and bacterial Inoculants on SPAD Index Values of Coriander

SPAD Index Values at 25 DAS																
Si Sources	**No Microbes**				**SSB4**				**SSB7**				**ZSB**			
Si Levels (mg Si kg^{-1})	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**
0	22.25	22.10	22.30	22.22	26.46	26.56	26.97	26.66	24.77	24.53	24.64	24.65	22.48	22.30	22.45	22.41
50	27.12	24.42	30.28	27.27	35.67	29.75	37.91	34.44	32.27	25.88	35.23	31.12	27.82	25.02	30.79	27.88
100	27.96	25.55	31.98	28.49	37.59	32.56	40.31	36.82	34.01	27.75	36.19	32.65	31.05	26.06	33.11	30.07
Mean	25.78	24.02	28.18	25.99	33.24	29.62	35.06	32.64	30.35	26.05	32.02	29.47	27.12	24.46	28.78	26.79
Factors	**M**		**S**		**L**		**M x S**		**M x L**		**S x L**		**M x S x L**			
SEd	0.210		0.182		0.182		0.363		0.363		0.314		0.629			
LSD (*P*=0.05)	0.418		0.362		0.362		0.724		0.724		0.627		1.254			
SPAD Index Values at 50 DAS																
Si Sources	**No Microbes**				**SSB4**				**SSB7**				**ZSB**			
Si Levels (mg Si kg^{-1})	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**
0	19.15	19.02	19.19	19.12	24.50	24.65	24.76	24.64	21.32	21.11	21.21	21.21	19.34	19.19	19.32	19.29
50	23.34	21.02	26.06	23.47	30.70	25.60	34.12	30.14	27.77	22.27	32.39	27.48	23.95	21.53	26.49	23.99
100	24.06	21.99	27.52	24.52	34.56	30.47	35.68	33.57	33.19	23.01	34.78	30.33	26.72	22.42	28.49	25.88
Mean	22.18	20.67	24.26	22.37	29.92	26.91	31.52	29.45	27.43	22.13	29.46	26.34	23.34	21.05	24.77	23.05
Factors	**M**		**S**		**L**		**M x S**		**M x L**		**S x L**		**M x S x L**			
SEd	0.329		0.285		0.285		0.571		0.571		0.494		0.988			
LSD (*P*=0.05)	0.657		0.569		0.569		1.138		1.138		0.985		1.97			

DAS – Days After Sowing; RHA – Rice Husk Ash; SSB – Silicate Solubilizing Bacteria; ZSB – Zinc Solubilizing Bacteria; M – Microbes; S – Sources; L – Levels; SEd – Standard Error of difference; LSD – Least Significant Difference; SSB4 - Bacillus altitudinis; SSB7 - Pseudomonas gessardii; ZSB - Bacillus aryabhattai

Table 3. Silicon Sources and bacterial Inoculants on Leaf Silicon (%) of Coriander

Leaf Silicon (%) at 25 DAS																
Si Sources	**No Microbes**				**SSB4**				**SSB7**				**ZSB**			
Si Levels (mg Si kg^{-1})	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**
0	1.35	1.38	1.39	1.37	1.77	1.78	1.79	1.78	1.54	1.53	1.54	1.54	1.40	1.39	1.40	1.40
50	1.69	1.52	1.89	1.70	2.22	1.85	2.91	2.33	2.01	1.61	2.54	2.05	1.73	1.56	1.92	1.74
100	1.74	1.59	1.99	1.78	2.61	2.34	3.38	2.78	2.40	1.67	2.77	2.28	1.93	1.62	2.06	1.87
Mean	1.59	1.50	1.76	1.62	2.20	1.99	2.70	2.30	1.99	1.60	2.28	1.96	1.69	1.52	1.79	1.67
Factors	**M**		**S**		**L**		**M x S**		**M x L**		**S x L**		**M x S x L**			
SEd	0.032		0.027		0.027		0.055		0.055		0.048		0.095			
LSD (*P*=0.05)	0.063		0.055		0.055		0.109		0.109		0.095		0.189			
Leaf Silicon (%) at 50 DAS																
Si Sources	**No Microbes**				**SSB4**				**SSB7**				**ZSB**			
Si Levels (mg Si kg^{-1})	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**
0	2.03	2.01	2.03	2.02	2.59	2.61	2.62	2.61	2.26	2.23	2.24	2.24	2.05	2.03	2.04	2.04
50	2.47	2.22	2.76	2.48	3.25	2.71	3.61	3.19	2.94	2.36	3.30	2.86	2.53	2.28	2.80	2.54
100	2.55	2.33	2.91	2.59	3.82	3.42	4.11	3.78	3.36	2.43	3.56	3.12	2.83	2.37	3.01	2.74
Mean	2.35	2.19	2.57	2.37	3.22	2.91	3.45	3.19	2.85	2.34	3.03	2.74	2.47	2.23	2.62	2.44
Factors	**M**		**S**		**L**		**M x S**		**M x L**		**S x L**		**M x S x L**			
SEd	0.047		0.040		0.040		0.081		0.081		0.070		0.140			
LSD (*P*=0.05)	0.093		0.081		0.081		0.161		0.161		0.140		0.279			

DAS – Days After Sowing; RHA – Rice Husk Ash; SSB – Silicate Solubilizing Bacteria; ZSB – Zinc Solubilizing Bacteria;
M – Microbes; S – Sources; L – Levels; SEd – Standard Error of difference; LSD – Least Significant Difference;
SSB4 - Bacillus altitudinis; SSB7 - Pseudomonas gessardii; ZSB - Bacillus aryabhattai

Table 4. Silicon Sources and bacterial Inoculants on Leaf Yield (g plant^{-1}) of Coriander

Si Sources / Si Levels (mg Si kg^{-1})	No Microbes				SSB4				SSB7				ZSB			
	$CaSiO_3$	$MgSiO_3$	RHA	Mean	$CaSiO_3$	$MgSiO_3$	RHA	Mean	$CaSiO_3$	$MgSiO_3$	RHA	Mean	$CaSiO_3$	$MgSiO_3$	RHA	Mean
0	4.35	4.32	4.36	4.34	5.57	5.60	5.63	5.60	4.84	4.80	4.82	4.82	4.39	4.36	4.39	4.38
50	5.30	4.77	5.92	5.33	6.97	5.82	7.67	6.82	6.31	5.06	7.13	6.17	5.44	4.89	6.02	5.45
100	5.47	5.00	6.25	5.57	7.56	6.51	8.24	7.44	6.84	5.23	7.39	6.49	6.07	5.09	6.47	5.88
Mean	5.04	4.70	5.51	5.08	6.70	5.98	7.18	6.62	6.00	5.03	6.45	5.82	5.30	4.78	5.63	5.24
Factors	**M**		**S**		**L**		**M x S**		**M x L**		**S x L**		**M x S x L**			
SEd	0.041		0.035		0.035		0.071		0.071		0.061		0.123			
LSD (*P*=0.05)	0.081		0.071		0.071		0.141		0.141		0.122		0.244			

DAS – Days After Sowing; RHA – Rice Husk Ash; SSB – Silicate Solubilizing Bacteria; ZSB – Zinc Solubilizing Bacteria; M – Microbes; S – Sources; L – Levels; SEd – Standard Error of difference; LSD – Least Significant Difference; SSB4 - Bacillus altitudinis; SSB7 - Pseudomonas gessardii; ZSB - Bacillus aryabhattai

Table 5. Silicon Sources and bacterial Inoculants on Adsorbed Silicon (mg kg^{-1}) in Soil

Ad-Si (mg kg^{-1}) at 25 DAS																
Si Sources	**No Microbes**				**SSB4**				**SSB7**				**ZSB**			
Si Levels (mg Si kg^{-1})	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**
0	12.25	12.16	12.27	12.23	15.66	15.76	15.83	15.75	13.63	13.50	13.56	13.56	12.37	12.27	12.36	12.33
50	14.92	13.44	16.66	15.01	19.63	16.37	23.22	19.74	17.76	14.24	20.71	17.57	15.31	13.77	16.94	15.34
100	15.38	14.06	17.60	15.68	24.00	19.48	27.10	23.53	21.22	14.72	23.52	19.82	17.09	14.34	18.22	16.55
Mean	14.18	13.22	15.51	14.31	19.77	17.21	22.05	19.67	17.54	14.15	19.26	16.98	14.92	13.46	15.84	14.74
Factors	**M**		**S**		**L**		**M x S**		**M x L**		**S x L**		**M x S x L**			
SEd	0.119		0.103		0.103		0.206		0.206		0.178		0.356			
LSD (*P*=0.05)	0.237		0.205		0.205		0.410		0.410		0.355		0.710			

Ad-Si (mg kg^{-1}) at 50 DAS																
Si Sources	**No Microbes**				**SSB4**				**SSB7**				**ZSB**			
Si Levels (mg Si kg^{-1})	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**	**$CaSiO_3$**	**$MgSiO_3$**	**RHA**	**Mean**
0	17.91	17.79	17.95	17.88	22.91	23.05	23.16	23.04	19.94	19.75	19.83	19.84	17.90	17.95	18.07	17.97
50	21.10	19.66	23.54	21.43	28.71	23.94	33.96	28.87	25.97	20.83	30.29	25.70	22.40	20.14	24.78	22.44
100	22.50	20.56	25.74	22.94	34.41	28.50	39.63	34.18	31.04	21.52	34.40	28.99	24.99	20.97	26.65	24.20
Mean	20.51	19.34	22.41	20.75	28.68	25.17	32.25	28.70	25.65	20.70	28.18	24.84	21.76	19.69	23.17	21.54
Factors	**M**		**S**		**L**		**M x S**		**M x L**		**S x L**		**M x S x L**			
SEd	0.144		0.125		0.125		0.249		0.249		0.216		0.432			
LSD (*P*=0.05)	0.287		0.248		0.248		0.497		0.497		0.430		0.860			

DAS – Days After Sowing; RHA – Rice Husk Ash; SSB – Silicate Solubilizing Bacteria; ZSB – Zinc Solubilizing Bacteria;
M – Microbes; S – Sources; L – Levels; SEd – Standard Error of difference; LSD – Least Significant Difference;
SSB4 - Bacillus altitudinis; SSB7 - Pseudomonas gessardii; ZSB - Bacillus aryabhattai

Table 6. Silicon Sources and bacterial Inoculants on Total Soluble Sugar (mg g^{-1} DW) of Coriander

Si Sources / Si Levels (mg Si kg^{-1})	No Microbes				SSB4				SSB7				ZSB			
	$CaSiO_3$	$MgSiO_3$	RHA	Mean	$CaSiO_3$	$MgSiO_3$	RHA	Mean	$CaSiO_3$	$MgSiO_3$	RHA	Mean	$CaSiO_3$	$MgSiO_3$	RHA	Mean
0	21.16	21.01	21.20	21.12	24.23	24.30	24.38	24.30	22.91	23.00	23.00	22.97	21.37	21.20	21.35	21.31
50	23.98	23.22	24.85	24.02	30.78	25.97	34.21	30.32	28.97	24.61	31.83	28.47	25.02	23.79	25.56	24.79
100	26.58	24.29	30.40	27.09	36.10	30.29	38.23	34.87	32.01	25.42	35.02	30.82	29.52	24.77	31.48	28.59
Mean	23.91	22.84	25.49	24.08	30.37	26.85	32.27	29.83	27.96	24.34	29.95	27.42	25.30	23.25	26.13	24.89
Factors	**M**		**S**		**L**		**M x S**		**M x L**		**S x L**		**M x S x L**			
SEd	0.181		0.157		0.157		0.313		0.313		0.271		0.542			
LSD (*P*=0.05)	0.361		0.312		0.312		0.624		0.624		0.541		1.082			

DAS – Days After Sowing; DW – Dry Weight; RHA – Rice Husk Ash; SSB – Silicate Solubilizing Bacteria; ZSB – Zinc Solubilizing Bacteria;
M – Microbes; S – Sources; L – Levels; SEd – Standard Error of difference; LSD – Least Significant Difference;
SSB4 - Bacillus altitudinis; SSB7 - Pseudomonas gessardii; ZSB - Bacillus aryabhattai

3.6 Total Soluble Sugar (TSS)

Total Soluble Sugar content of Coriander dry leaves ranged from 21.01 to 38.23 mg g^{-1} DW (Table 6). Application of Rice Husk Ash @ 100 mg Si kg^{-1} with SSB4 showed a maximum soluble sugar content while control or without microbes and without Si source displayed a minimum value. Silicon sources increased the total soluble sugar of coriander leaves which is in the sequence of $MgSiO_3$ < $CaSiO_3$ < RHA. TSS showed linear improvement with the increased Si levels. The mean TSS values ranged from 22.84 to 26.85 mg g^{-1} DW, 23.91 to 30.37 mg g^{-1} DW, and 25.49 to 32.27 mg g^{-1} DW for $MgSiO_3$, $CaSiO_3$, and RHA respectively. TSS content was increased by the microbial strains in the sequence of without bacteria < ZSB < SSB7 < SSB4. Afshari et al., [24] observed that the foliar application of silicon sources increased the total soluble sugar content in coriander leaves. Many findings showed that in sorghum [30], soybean [31], rice [32], cucumber [33], sugarcane [34], maize [35], pepper [36], and barley [37], an improvement in TSS content with the help of Si fertilizers. SSB4 dissolved more Si from the soil compared to SSB7 and ZSB which might have helped in improving the TSS content in coriander leaves compared to other microbial strains.

4. CONCLUSION

The present investigation clearly indicated the significant effect of integration of Si sources with microbial inoculants in sandy loam soil of low soil adsorbed Si status. The application of Si sources alone and in combination with SSB/ZSB enhanced the growth parameters in terms of plant height and SPAD index values, leaf Si content, coriander leaf yield, and leaf quality besides improving the soil fertility. The plant height increased with the stage of the crop due to the applied Si sources and SSB whereas the SPAD index values were higher at 25 DAS compared to 50 DAS. The leaf silicon ranged from 1.35 to 3.38 per cent at 25 DAS, whereas it varied from 2.01 to 4.11 per cent. The Coriander leaf yield ranged from 4.32 to 8.24 g $plant^{-1}$. The application of RHA @ 100 mg Si kg^{-1} with SSB4 recorded the highest leaf yield of 8.24 g $plant^{-1}$ followed by RHA @ 50 mg Si kg^{-1} with SSB4. However, the latter produced a comparable leaf yield with $CaSiO_3$ @ 100 mg Si kg^{-1}. A similar trend was clearly evident with soil adsorbed Si. The leaf yield increase over control for RHA @ 100 mg Si kg^{-1} + SSB4 was the highest (88.92%) followed by RHA @ 50 mg Si kg^{-1} with SSB4 (76.58%) and $CaSiO_3$ @ 100 mg Si kg^{-1} + SSB4 (73.82%). The results indicated that the application of SSB was found to be effective in enriching the Si content of coriander leaf, besides increasing the yield.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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