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Study the Role of Silicon-Solubilizing Bacteria pest Resistance in Enhancing Silicon Concentration, Uptake by Rice, and Soil Microbial Parameters

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Approximately 800 insect pest species attack rice (Oryza sativa L.), which is farmed on roughly 20% of the world's arable land. An increase in insect resistance may be achieved if silicon, an abiotic elicitor, were to enhance jasmonic acid synthesis in rice plants. Several studies have investigated the possibility of utilizing silicon fertilizer to suppress rice pests by increasing crop resilience. Restoring environmental quality could be aided by this. Some studies have shown that resistant rice accessions may increase silica absorption, which in turn protects stems against yellow stem borer larvae. Because of its crucial role in plant nutrition, particularly during times of stress, silicon is now regarded as more of a "beneficial substance" or "quasi-essential" than a "necessary component" for plant growth. Within a rice cropping system, this experiment sought to determine the effects of different amounts of silicon application, bacteria that solubilize silicon, and techniques for rice establishment on soil microbial traits, soil silicon concentrations, and the amount of silicon absorbed by the rice.

Kerword: *Rice, Silicon, combination, pest, environmental*

1. Introduction

The another most common element on Earth after oxygen is silicon, which is found in most soils and is available to plants. Plants are not harmed by excessive Si buildup [1]. Although scientists have studied silicon's impact on plants for more than a century, it wasn't until the early 1900s that they realized how much silicon may increase agricultural output [2]. Japanese scientists looked at whether silicon has an impact on the regularity of rice harvests. An early Si research by Onodera was published in a reputable agronomic journal [3]. He found that compared to healthy leaves from the same field, blast-infected rice leaves from many Japanese farms had a lower Si content. He discovered that the amount of silicon in healthy rice tissues varied depending on the paddy field. Despite the fact that these findings have prompted several studies on its effects, silicon (Si) is not necessary for plant development. A vital component of agriculture, silica promotes crop development and plant resistance to biotic and abiotic stressors. The usage of pesticides and fungi may be decreased with silicon fertilizer. Environmentalists are becoming more and more interested in Si [4,5,6,7].

Si seems to enhance vegetative growth, plant development, productivity, and stress mitigation [8–11]. Numerous plant species have long been recognized to be impacted by Si treatment. Other advantages of Si include a faster rate of photosynthetic activity, less transpiration, and resistance to UV-B radiation [12]. Diseases, insect pests, drought, floods, salt, and metal toxicity are just a few of the biotic and abiotic challenges that plants must deal with. Silicon is necessary for plant development in the majority of agricultural soils [12,13,14]. Silica is a common nutrient used in plant response testing. High levels of Si may be actively absorbed and retained by certain dicots, monocots, and vegetable and fruit crops [6,15]. Take into account crop requirements, soil moisture, crop nutrient uptake, and soil quality before applying Si fertilizer. This controls how well crops absorb nutrients from the soil [9]. Fertilizers containing silicon are claimed to increase plant growth, hardiness, disease resistance, and yields [7,10,11]. Rice (Oryza sativa) exhibited increased culm wall thickness, vascular bundle size, and peroxidase activity after Si fertilization, which improved lodging avoidance, stress tolerance, and stem strength [16,17]. Proline levels may rise when fertilizer Si is applied to water-stressed upland rice cultivars during the vegetative and reproductive phases, indicating stress tolerance [18]. Si may also help drought-stressed maize (Zea mays) plants by increasing water consumption efficiency. due to the fact that it reduces transpirational water loss and enhances xylem vessel water flow [19–25].

Climate change is one of several worldwide threats to agricultural species. It worsens biotic and abiotic stressors and drastically lowers agricultural yield. By 2050, food resources will be diminished due to global population increase [26]. In order to boost agricultural output, several management strategies are needed. Food supply and the planet depend on sustainability. In this case, using Si fertilizer in conjunction with other fertilizer modifications may alter a variety of plant characteristics and improve the production and health of the plants. We all know that silicon fertilizer affects crop growth, quality, and yield. Because they are non-corrosive and non-polluting, silica fertilizers, both organic and inorganic, are environmentally beneficial. Because they are inexpensive, they are often to as "smart fertilisers." Plant nutrient absorption is enhanced and soil pH is adjusted by silica-based fertilizers made from slag or silicon-containing mineral ores [27].

Soil contains silicon

One typical component of soil solutions is polysilicic acid, while another is oligomeric silicon or monomeric silicon (H_4SiO_4, the form that plants may use). Oligomeric silica consists of two or more chains of H_4SiO_4 that may be up to ten silicon atoms long, while polymeric silica is associated with a higher degree of polymerization. While monosilicic acid helps plants eat and absorb nutrients, polysilicic acid affects soil aggregation. Soil solutions may be able to absorb solid phases like clay particles and Fe and Al hydroxides depending on the quantities of dissolved silicic acid, according to Sommer et al. (2006) [28]. Secondary clay minerals may draw silicon from soil solutions, as stated by Siever and Woodford (1973) [29]. The high adsorption capacity of Fe and Al hydroxides allows for the extraction of a large amount of dissolved silicon from soil solutions (McKeague and Cline, 1963; Cornell and Schwertmann 1996 [30,31].

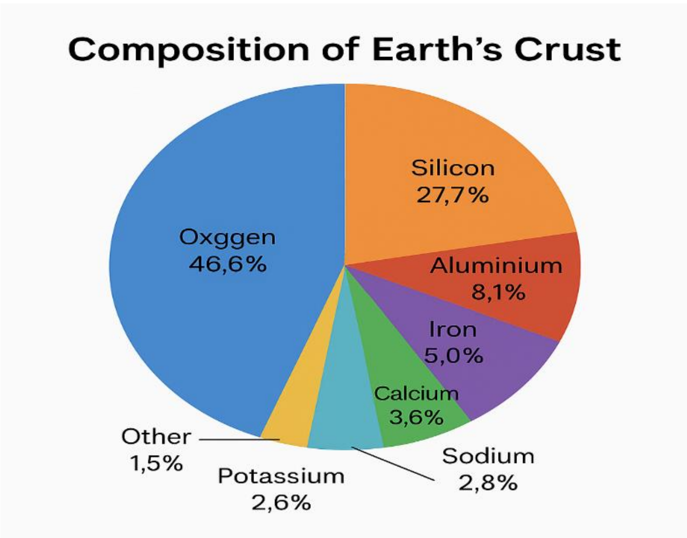

Figure 1: Elements that make up the Earth's crust and their relative proportions.

The Soil Silica Cycle

All three states of soil-bound silicon—solid, liquid, and adsorbed—are necessary for the cycle to function. Plants and microbes only absorb the uncharged form of H_4SiO_4, which is part of the polymerised, complexed silicic acid and H_4SiO_4 in soil solution forms of liquid silicon. Polymerised silica is deposited inside plant tissues or microbial cellular structures as a secondary outcome of silicon absorption. Litter and microbial decay return polymerised silica bodies to the topsoil, where they add to the soluble biogenic silica pool and increase the soil solution's silicon availability. Soil silicon is enhanced during decomposition of silicon-rich manure, which is applied to soils via compost and manure. Ionic, molecular, and aggregate silicon are all possible components of the natural fluids used for irrigation. As a result of atmospheric deposition, which includes the movement of dust, ash, and rain, silicon may be introduced to soil (Struyf et al., 2009) [32].

Study Objective

1. To study things of different quantities of silicon application and techniques for rice establishment
2. To study rice-growing systems, we want to learn how bacteria that break down silicon affect soil microbes, silicon levels, and rice uptake.

MATERIALS AND METHODS

The Indian Agricultural Research Institute research farm conducted a field experiment in 2023 and 2024 kharif. The sandy clay loam soil used for the experiment had a pH of 8.32, 0.55% organic carbon, 266 kg/ha silicon, 166.0 kg/ha nitrogen, 16.54 kg/ha phosphorus, and 254.2 kg/ha potassium.

Three studies employed split-split plots. Twenty-four therapy combinations were studied. Three rice-planting methods were exhibited in the main allotment. Four silicon application steps are shown on the subplot. The sub-plot showed sulfur-oxidizing bacteria. Aerobic rice (AR), transplanted rice (TPR), and rice intensification system were the primary plot treatments in this rice harvest. Rice crops were peripherally treated with four silicon dosages (0, 40, 80, and 120 kg/ha) and two silicon-solubilizing bacteria, Bacillus sp. and Pseudomonas sp. Pusa Basmati 1509 rice was seeded at the prescribed rate under TPR and AR conditions. Using urea, 120 N kg/ha of nitrogen fertilizer was applied in three equal sections. Nitrogen was applied during puddling and three weeks after transplanting, when the crop was in panicle initiation. The final puddling method used 60 kg/ha di-ammonium phosphate for phosphorus and muriate of potash for potassium.

All groups except one got a baseline Si dose via broadcasting before rice transplanting per procedure. The control group received no Si treatment. Treatment of seeds and seedlings introduced silicon-degrading bacteria. We crushed wheat and straw samples for treatment in a Willey mill with stainless steel blades to make a fine powder. The samples were cooked at 60–70°C to guarantee consistent weight. The grain and chaff silicon content was determined spectrophotometrically (Ma and Tamai 2002). We examined ground plant nutrients. A core sampler took soil samples from each plot. Placing small plastic containers with samples 0–15 cm deep near plant roots is great. Air-dried, powdered, and sieved soil samples with Aaleksandrov media with a 2 mm mesh. Pre- and post-culture microbial biomass carbon (MBC) and bacteria, fungus, and actinomycetes were measured. Soil enzyme activity, including dehydrogenase, and silicon-solubilizing microorganisms were also assessed.

DATA ANALYSIS AND RESULTS

In Table 1, TPR had the highest grain production (5.10 t/ha) and panicle density (288.0/m2) among the five rice establishment methods tested for two years. Aerobic and SRI rice yields were lowest in panicle density and grain output. The statistical changes in grain output were comparable for TPR and SRI, although both yielded more than aerobic rice. Hossain et al. (2001) tested a variety of silicon fertilizers on pot-grown peddy. They found that rice straw increased silicon content in the plants. Rice straw in the soil or with organic matter may boost harvest yields.

Table 1: Procedure for Establishing Rice

Treatment	No. of panicles/ m^2	Grain yield (t /ha)	Microbial biomass carbon (µg/g soil)	Dehydrogenase activity (µg TPF/ g soil/day)	Total count of silicon solubilizing bacteria (× 10^2 cfu/g soil)
Rice Establishment Method					
TPR	288.0	5.10	258.0	165.0	215.0
AR	245.0	4.45	290.0	202.0	243.0
SRI	291.0	4.90	275.0	182.0	235.0

Silicon Application Level					
Control	255.0	4.45	255.0	168.0	212.0
40 kg/ha	267.0	4.70	270.0	180.0	225.0
80 kg/ha	278.0	4.95	282.0	188.0	237.0
120 kg/ha	281.0	5.05	290.0	192.0	241.0
Bacteria That Solubilize Silicon					
Bacillus	273.0	4.85	278.0	185.0	235.0
Pseudomonas	268.0	4.70	270.0	179.0	225.0
SEm ±	2.7	0.05	2.9	1.8	2.9
LSD (P = 0.05)	NS	NS	NS	NS	6.8
Interaction	NS	NS	NS	NS	NS

The silicon content of rice straw fertilizer may not be immediately accessible, but Japanese research show that it rises to over 70% after 40 years. Because agricultural plants eat inorganic silicates soon after fertilization, they affect yields quickly. This explains their widespread use, according to Ma and Takahashi (2002). Rice Intensification System (SRI) yields the most panicles/m² (291), resulting in a decent quantity of grain (4.90 t/ha). Transplanting increases soil microbial activity, yields (5.10 t/ha), and carbon- and silicon-solubilizing bacteria. Alternate Wetting and Drying (AR) exhibited the highest microbial biomass carbon and dehydrogenase activity, indicating better soil health but lower yield. Si fertilisation increased tiller count, dry leaf weight, 1000-grain weight, yield, and stem and leaf Si content, according to Gholami and Falah (2013). Rice roots and shoots' dry weight increased with silicon supplementation. Adding silicon-dispersing bacteria to seeds or seedlings did not reduce grain yield in either year. Bacillus inoculation affected grain production more than Pseudomonas.

Kappaphycus alvarezii sap-enriched biochar greatly boosted beneficial soil biota, notably AMF. Rakian et al. (2024) found that acidic soils helped highland rice grow and produce. Ybraikozha et al. (2024) found that biological preparations like Phytop 8.67 increased rice yields in saline soils by 25-30% by improving plant viability and seed germination. Soil pH, organic matter concentration, and clay content affect rice yield. Suryanto et al. (2020) observed that certain rice varieties performed better on optimal soils.

Table 2: Procedure for Determining Rice

Treatment	Si concentration in grain (%)	Si concentration in straw (%)	Si uptake by grain (kg/ha)	Si uptake by straw (kg/ha)	Total Si uptake (kg/ha)
TPR	1.50	3.80	75.2	248.5	77.8
AR	1.62	4.10	71.0	248.9	73.5
SRI	1.38	3.90	68.5	251.2	70.1
SEm ±	0.03	0.06	2.2	7.9	2.3
LSD (P = 0.05)	0.12	0.26	NS	NS	8.8
Application Level of Silicon (kg/ha)					
Control	1.35	3.75	59.0	220.0	55.0
40	1.42	3.85	65.5	239.0	61.5
80	1.58	4.05	76.5	260.0	78.5
120	1.65	4.10	81.0	267.5	85.0
SEm ±	0.02	0.06	2.0	7.2	2.0
LSD (P = 0.05)	0.07	0.18	5.8	21.0	5.5
Microbes That Solubilize Silicon					
Bacillus	1.50	4.00	72.0	252.0	74.0
Pseudomonas	1.46	3.95	68.8	242.5	70.3

SEm ±	0.02	0.05	1.5	4.8	1.5
LSD (P = 0.05)	NS	NS	NS	NS	NS
Interaction	NS	NS	NS	NS	NS

TPR, Transplanted rice; AR, Aerobic rice; SRI, System of rice intensification.

Silica content in grain and straw: Rice cultivation methods greatly affected silicon concentration (Table 2). Over the two-year study, aerobic rice grain and straw samples had the highest Si content and TPR the lowest. Silicon treatment rates considerably altered grain and straw Si content across the two-year trial. The greatest Si-concentration was 120 kg silicon/ha applied to grain (1.62%) and straw (4.10%), followed by 80 kg silicon/ha (1.58%) and 4.05% (statistically equivalent), respectively. Kim et al. (2012) discovered that 80 and 120 kg silicon/ha enhanced grain and straw Si concentrations more than the control and 40 kg silicon/ha in both years. Kim\ et\ al.\ (2012), Gholami and Falah (2013), and Emam (2014) found that Si enhances yield. Si reduces transpiration, improving plant water and nutrient use. Microorganisms that solubilize silicon did not affect grain or straw silicon content in any research year. Pseudomonas lagged behind Bacillus in the two-year research. Lauwers et al. (1974) mentioned Bacillus sp. Pati et al. (2016) found that 600 kg/ha or 50 kg/ha silicon boosts grain and straw yields. Straw and grain yields increased by 6,740 and 6183.3 kg/ha, respectively. 2020 (Arthi et al.).

How wheat grains and straw absorb silicon: Silicon absorption by grain, straw, and total rice harvests was consistent regardless of crop configuration. Table 1 shows that rice straw and grain absorbed silicon depending on silicon treatment quantity and rate. The best silicon absorption efficiency was 120 kg/ha for grain (81.0 kg/ha) and straw (267.5 kg/ha). Then, 80 kg/ha silicon was applied to grain (76.5 kg/ha) and straw (260.0 kg/ha) with statistically equivalent results. Compared to the control and 40\ kg\ silicon/ha in\ both\ years,\ 80\ and\ 120\ kg silicon/ha enhanced grain and straw Si-absorption and total intake. The silicon-soluble bacteria Bacillus and Pseudomonas did not affect grain and straw silicon absorption across the two-year study. Grain and straw yields may have changed between years (Singh et al. 2005). The Singh et al. (2006) findings support this. During the two-year investigation, bacteria that dissolve silicon did not affect grain and straw nitrogen, phosphorus, potassium, and silicon levels. Silicon-rich plants absorb more nitrogen, phosphate, and potassium, improving plant health and production, according to Pati et al. (2016) and Mobasser et al. (2022). Research shows that soil silicon increases grain and straw yields more than topically administered silicon (Arthi et al., 2021). The method of silicon delivery seems to considerably impact its effectiveness.

Findings:

The AR and SRI produced the lowest grain yields, whereas transplanted rice (TPR) produced the highest yields (5.10 t/ha). Regardless, signs of improved soil biological quality, including increased MBC, dehydrogenase activity, and bacteria that solubilize silicon, were seen in AR.

Application of silicon at a rate of 120 kg/ha significantly improved grain production, MBC, dehydrogenase activity, and silicon absorption in both grain and straw. Regardless of the figure, both 80 and 120 kg/ha have their advantages.

Microorganisms That Degrade Silicon: When inoculated with Bacillus and Pseudomonas, neither the grain yield nor the absorption of silicon were impacted. In terms of enhancing the soil's microbial properties, however, Bacillus species performed somewhat better than other categories.

Conclusion:

Three distinct methods of establishment were considered: Aerobic Rice (AR), the System of Rice Intensification (SRI), and transplanted rice (TPR). The grain output was lowest in TPR and SRI, followed by AR, with TPR having the maximum yield at 5.10 t/ha. Despite this, AR exhibited better soil biological properties, including MBC, dehydrogenase activity, and the number of microbes that could dissolve silicon. At 120 kg/ha of silicon, after an application of 80 kg/ha, the grain and straw absorbed the most silicon, with rates of 81.0 kg/ha and 267.5 kg/ha, respectively. Comparisons with the control and 40 kg/ha treatments showed significantly lower rates for these two.

Enhanced soil microbiological characteristics, a sign of healthier soil, were also a result of these higher silicon treatment rates. Grain yield and silicon absorption were unaffected by genetic engineering using microorganisms that solubilize silicon, such as Bacillus and Pseudomonas species. Bacillus species and Pseudomonas species differed little in their ability to enhance soil microbial properties. A combination of various crop establishment procedures, such TPR, with silicon fertilisation at rates of 80-120 kg/ha may increase soil biological health and rice output. Despite the little impact on yield, more investigation into the role of silicon-solubilizing bacteria in soil health is required.

Future Perspectives

(i) Showing how Si fertilisers and pure Si are useful under extreme conditions. Hence, it is important to investigate the effects of Si or Si fertiliser devoid of inorganic ions like Mg and Ca in typical settings, as there is a dearth of study on this topic.

(ii) Promises that will be fulfilled. There has to be consistent investigation into crop-specific Si accumulators and soil pH in order to determine the optimal rate and dose of Si fertiliser application.

(iii) Naytech has the potential to have far-reaching consequences for the future of agriculture. There hasn't been much study of using nanotechnology to farming, thus researchers should look at novel nanoparticle ways to make NSi that can boost the catalytic activity of Si fertilisers. It is equally important to prioritise research into the freshly found materials' toxicity, sustainability, mobility, efficiency, and particle integrity.

(iv) After the new NSi has been tested in exploratory research to determine its feasibility, release date, cost, scaling factors, and unexpected consequences, it should be evaluated in large or actual fields to determine its consistency and performance.

On a global scale, climate change is anticipated to bring about new constraints and production penalties for large and small crops alike, while also creating chances to sustain output. Fertiliser treatments with silicon (Si) are common in many regions, but there needs to be more global knowledge in order to maximise the benefits of these applications and close the gap between farmers and scientists. To mitigate biotic and abiotic stress in the future, we think our study could provide light on Si fertilisers and their potential agricultural applications.

Reference

1. Ma, J.F.; Takahashi, E. Soil, Fertilizer, and Plant Silicon Research in Japan, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2002; pp. 1–294. ISBN 9780080525761.
2. Ma, J.F.; Yamaji, N. Silicon uptake and accumulation in higher plants. Trends Plant Sci. 2006, 11, 392–397.
3. Onodera, I. Chemical studies on rice blast. J. Sci. Agric. Soc. 1917, 180, 606–617.
4. Savant, N.K.; Datnoff, L.E.; Snyder, G.H. Depletion of plant-available silicon in soils: A possible cause of declining rice yields. Commun. Soil Sci. Plant Anal. 1997, 28, 1245–1252.
5. Datnoff, L.; Rodrigues, F. The Role of Silicon in Suppressing Rice Diseases. APSnet Feature Artic. 1997, 58.
6. Luyckx, M.; Hausman, J.-F.; Lutts, S.; Guerriero, G. Silicon and Plants: Current Knowledge and Technological Perspectives. Front. Plant Sci. 2017, 8, 411.
7. Thakral, V.; Bhat, J.A.; Kumar, N.; Myaka, B.; Sudhakaran, S.; Patil, G.; Sonah, H.; Shivaraj, S.M.; Deshmukh, R. Role of silicon under contrasting biotic and abiotic stress conditions provides benefits for climate smart cropping. Environ. Exp. Bot. 2021, 189, 104545.
8. Navarro-Torre, S., Rodríguez-Llorente, I. D., Pajuelo, E., Mateos-Naranjo, E., Redondo-Gómez, S., and Mesa-Marín, J.. (2023). "Role of bacterial endophytes in plant stress tolerance: Current research and future outlook," in Microbial endophytes and plant growth, eds. M. K. Solanki et al. (Academic Press, 125 London Wall, London EC2Y 5AS, United Kingdom) 35–49.
9. Orozco-Mosqueda, M., del Carmen, G. S., and Bernard, R. G. (2023). Recent advances in the bacterial phytohormone modulation of plant growth. Plant 12:606. doi: 10.3390/plants12030606

10. Raza, T., Abbas, M., Imran, S., Khan, M. Y., Rebi, A., Rafie-Rad, Z., et al. (2023). Impact of silicon on plant nutrition and significance of silicon mobilizing bacteria in agronomic practices. Silicon. doi: 10.1007/s12633-023-02302-z
11. Alharbi, K., Osman, H. S., Rashwan, E., Hafez, E. M., and Omara, A. E. D. (2022). Stimulating the growth, anabolism, antioxidants, and yield of rice plants grown under salt stress by combined application of bacterial inoculants and nano-silicon. Plants 11:3431. doi: 10.3390/plants11243431
12. Ali, M. G., Ahmed, M., Ibrahim, M. M., El Baroudy, A. A., Ali, E. F., Shokr, M. S., et al. (2022). Optimizing sowing window, cultivar choice, and plant density to boost maize yield under RCP8. 5 climate scenario of CMIP5. Int. J. Biometeorol. 66, 971–985. doi: 10.1007/s00484-022-02253-x
13. Mahmood, S., Daur, I., Yasir, M., Waqas, M., and Hirt, H. (2022). Synergistic practicing of rhizobacteria and silicon improve salt tolerance: implications from boosted oxidative metabolism, nutrient uptake, growth and grain yield in mung bean. Plants 11:1980. doi: 10.3390/plants11151980
14. Roy, C. A., Roy, S. K., Trivedi, P., Choi, J., Cho, K., Yun, S. H., et al. (2022). Label-free proteomics approach reveals candidate proteins in rice (Oryza sativa L.) important for ACC deaminase producing bacteria-mediated tolerance against salt stress. Environ. Microbiol. 24, 3612–3624. doi: 10.1111/1462-2920.15937
15. Shaffique, S., Khan, M. A., Wani, S. H., Pande, A., Imran, M., Kang, S. M., et al. (2022). A review on the role of endophytes and plant growth promoting rhizobacteria in mitigating heat stress in plants. Microorganisms 10, 1286. doi: 10.3390/microorganisms10071286.
16. Dorairaj, D.; Ismail, M.R. Distribution of silicified microstructures, regulation of cinnamyl alcohol dehydrogenase and lodging resistance in silicon and paclobutrazol mediated Oryza sativa. Front. Physiol. 2017, 8, 491.
17. Ma, J.F.; Takahashi, E. Chapter 4—Effect of silicate fertilizer application on paddy rice. In Soil, Fertilizer, and Plant Silicon Research in Japan; Ma, J.F., Takahashi, E., Eds.; Elsevier Science: Amsterdam, The Netherlands, 2002; pp. 49–61.
18. Mauad, M.; Crusciol, C.A.C.; Nascente, A.S.; Grassi Filho, H.; Lima, G.P.P. Effects of silicon and drought stress on biochemical characteristics of leaves of upland rice cultivars. Rev. Ciência Agronômica 2016, 47, 532–539.
19. Maghsoudi, K.; Emam, Y.; Pessarakli, M. Effect of silicon on photosynthetic gas exchange, photosynthetic pigments, cell membrane stability and relative water content of different wheat cultivars under drought stress conditions. J. Plant Nutr. 2016, 39, 1001–1015.
20. Gao, X.; Zou, C.; Wang, L.; Zhang, F. Silicon decreases transpiration rate and conductance from stomata of maize plants. J. Plant Nutr. 2006, 29, 1637–1647.
21. 16. Gao, X.; Zou, C.; Wang, L.; Zhang, F. Silicon improves water use efficiency in maize plants. J. Plant Nutr. 2005, 27, 1457–1470.
22. Murillo-Amador, B.; Yamada, S.; Yamaguchi, T.; Rueda-Puente, E.; Ávila-Serrano, N.; García-Hernández, J.; López-Aguilar, R.; Troyo-Diéguez, E.; Nieto-Garibay, A. Influence of calcium silicate on growth, physiological parameters and mineral nutrition in two legume species under salt stress. J. Agron. Crop Sci. 2007, 193, 413–421.
23. Reynolds, O.L.; Padula, M.P.; Zeng, R.; Gurr, G.M. Silicon: Potential to promote direct and indirect effects on plant defense against arthropod pests in agriculture. Front. Plant Sci. 2016, 7, 744.
24. 19. Han, Y.; Lei, W.; Wen, L.; Hou, M. Silicon-mediated resistance in a susceptible rice variety to the rice leaf folder, Cnaphalocrocismedinalis Guenée (Lepidoptera: Pyralidae). PLoS ONE 2015, 10, e0120557.
25. Keeping, M.G.; Kvedaras, O.L.; Bruton, A.G. Epidermal silicon in sugarcane: Cultivar differences and role in resistance to sugarcane borer Eldana saccharina. Environ. Exp. Bot. 2009, 66, 54–60.
26. Ray, D.K.; Mueller, N.D.; West, P.C.; Foley, J.A. Yield trends are insufficient to double global crop production by 2050. PLoS ONE 2013, 8, e66428.
27. Liang, Y.; Nikolic, M.; Bélanger, R.; Gong, H.; Song, A. Effect of Silicon on Crop Growth, Yield and Quality. In Silicon in Agriculture: From Theory to Practice; Liang, Y., Nikolic, M., Bélanger, R., Gong, H., Song, A., Eds.; Springer Netherlands: Dordrecht, The Netherlands, 2015; pp. 209–223.

28. Sommer M, Kaczorek D, Kuzyakov Y, Breuer J. Silicon pools and fluxes in soils and landscapes - A review. J Plant Nutr Soil Sci. 2006;169:310-329.
29. Siever R, Woodford N. Sorption of silica by clay minerals. Geochim Cosmochim Acta. 1973;37:1851-1880.
30. McKeague JA, Cline MG. Silica in soil solutions. I. The form and concentration of dissolved silica in aqueous extracts of some soils. Can J Soil Sci. 1963;43:70-82.
31. Cornell RM, Schwertmann U. The iron oxides: structure, properties, reactions, occurrence and uses. Weinheim/New York: VCH; c1996.
32. Struyf E, Smis A, Damme SV, Meire P, Conley DJ. The global biogeochemical silicon cycle. Silicon. 2009;1:207-213.
33. Pati, S., Pal, B., Badole, S., Hazra, G. C., & Mandal, B. (2016). Effect of Silicon Fertilization on Growth, Yield, and Nutrient Uptake of Rice. Communications in Soil Science and Plant Analysis, 47(3), 284–290. https://doi.org/10.1080/00103624.2015.1122797
34. Arthi, M. V., Sriramachandrasekharan, R., & Manivannan, A. (2021). Enhancement of agronomic traits and yield of rice var. ADT 43 grown in typic ustifluvent soil through silicon fertilization. Journal of Applied and Natural Science, 13(3), 1052–1058. https://doi.org/10.31018/JANS.V13I3.2803
35. Mobasser, H. R., Petrodi, E. R., & Rezvani, M. (2022). Silicon and Zinc Improves Grain Yield and Nutrient Status in Rice When Supplied During the Different Growth Stages. Romanian Agricultural Research, 39, 371–383. https://doi.org/10.59665/rar3934.
36. Rakian, T. C., Kilowasid, L. M. H., Afa, L. O., RISKYANA, A., NURAZIZAH, N., Wijayanti, Y., Bahrun, A., SUBAIR, I., RAHNI, N. M., Alam, S., SARAWA, S., & KARIMUNA, L. (2024). Soil biological quality in rhizosphere, growth, and yield of upland rice grown on acid soil after amended biochar enriched sap of Kappaphycus alvarezii. <i>Biodiversitas</i>, <i>24</i>(12). https://doi.org/10.13057/biodiv/d241241</div>
37. Ybraikozha, N., Toktamysov, A., Sagindykova, E., Bissenova, L., Eleuova, E. Sh., Bugubaeva, A. U., Nugmanov, A., Ekibaeva, G., Chashkov, V., & Tokusheva, A. (2024). Effect of the Biological Preparation Phytop 8.67 on the Quality and Yield of Rice in Saline Soils. *Online Journal of Biological Sciences*. https://doi.org/10.3844/ojbsci.2024.41.47
38. Suryanto, P., Taryono, T., Supriyanta, S., Kastono, D., Putra, E. T. S., Handayani, S., Widyawan, M. H., & Alam, T. (2020). Assessment of soil quality parameters and yield of rice cultivars in Melaleuca cajuputi agroforestry system. *Biodiversitas*, *21*(8). https://doi.org/10.13057/BIODIV/D210807
39. Rakian, T. C., Kilowasid, L. M. H., Afa, L. O., RISKYANA, A., NURAZIZAH, N., Wijayanti, Y., Bahrun, A., SUBAIR, I., RAHNI, N. M., Alam, S., SARAWA, S., & KARIMUNA, L. (2024). Soil biological quality in rhizosphere, growth, and yield of upland rice grown on acid soil after amended biochar enriched sap of Kappaphycus alvarezii. *Biodiversitas*, *24*(12). https://doi.org/10.13057/biodiv/d241241.
40. Emam M M, Khattab E H, Helal M N and Deraz E A. 2014. Effect of selenium and silicon on yield quality of rice plant grown under drought stress. Australian Journal of Crop Science 8: 596–605.
41. Epstein E. 1999. Silicon. Annual Review of Plant Physiology and Plant Molecular Biology 50: 641–4.
42. Gao X, Zou C, Wang L and Zhang F. 2006. Silicon decreases transpiration rate and conductance from stomata of maize plants. Journal of Plant Nutrition 29(9): 1637–47.
43. Gao X, Zou C, Wang L and Zhang F. 2005. Silicon Improves Water Use Efficiency in Maize Plants. Journal of Plant Nutrition 27(8): 1457–70.
44. Gholami Y and A Falah. 2013. Effects of two different sources of silicon on dry matter production, yield, and yield components of rice, Tarom Hashemi variety and 843 lines. International Journal of Agriculture and Crop Sciences 5: 227–31.
45. Hopkins D W and Shiel R S. 1996. Size and activity of soil microbial communities in long-term experimental grassland plots treated with manure and inorganic fertilizers. Biology and Fertility of Soils 22: 66–70.
46. Hossain K A, Horiuchi T and Miyagawa S. 2001 Effects of silicate materials on growth and grain yield of rice plants grown in clay loam and sandy loam soils. Journal of Plant Nutrition 24: 1–13.

47. Jawahar S and Vaiyapuri V. 2010. Effect of sulphur and silicon fertilization on growth and yield of rice. International Journal of Current Research. 9(1): 36–8.
48. Kim Y H, Khan A L, Shinwari Z K, Kim D H, Waqas M, Kamran M and Lee I J. 2012. Silicon treatment to rice (Oryza sativa L. cv 'gopumbyeo') plants during different growth period and its effect on growth and grain yield. Pakistan Journal of Botany 44: 891–97.
49. Lauwers A M and Heinen W. 1974. Biodegradation and utilization of silica and qurtz. Archiv für Mikrobiologie 95: 67–78.
50. Ma J F and Takahashi E. 2002. Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. Soil Science and Plant Nutrition 50(1): 11–8.
51. Ma J F and Yamaji N. 2006. Silicon uptake and accumulation in higher plants. Trends in Plant Science 11: 392–97.
52. Ma J F, Y Miyake and Takahashi E. 2001. Silicon as a beneficial element for crop plants. Silicon in Agriculture, pp 17–39. Elsevier Science Publishing, New York.
53. Narayanaswamy C and Prakash N B. 2009. Calibration and categorization of plant available silicon in rice soils of South India. Journal of Plant Nutrition 32(8): 1237–54.
54. Prakash N B. 2002. Status and utilization of silicon in Indian rice farming. Japanese Society of Soil Science and Plant Nutrition 1: 266–73.
55. Savant N K, Datnoff L E and Snyder G H. 1997. Depletion of plant available silicon in soils: a possible cause of declining rice yields. Communication in Soil Science and Plant Analysis 28: 1245–52.
56. Singh A K, Singh R and Singh K. 2005. Growth, yield, and economics of rice (Oryza sativa) as influenced by level and time of silicon application. Indian Journal of Agronomy 50: 190–3.
57. Singh K, Singh R, Singh J P, Singh Y and Singh K K. 2006. Effect of level and time of silicon application on growth, yield and its uptake by rice (Oryza sativa). Indian Journal of Agricultural Sciences 76(7): 410–13.
58. Yogendra N D, B H Kumara N, Chandra S, Prakash N B, Anatha M S and Jeyedeva H M. 2014. Effect of silicon on real time nitrogen management in a rice ecosystem. African Journal of Agricultural Research 9(9): 831–40.