Enhancing Crops Sustainably Through The Combined Use Of Microbiological And Silicon Resources

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ABSTRACT
As global food demand escalates due to a rapidly growing population, sustainable agricultural practices are essential to enhance crop productivity while minimizing environmental impact. This review explores the synergistic effects of silicon-solubilizing bacteria (SSB) and phosphate-solubilizing bacteria (PSB) in conjunction with silicon fertilizers on plant growth and yield. Silicon, the second most abundant element in the Earth's crust, plays a crucial role in improving soil health and enhancing plant resilience against abiotic stresses such as drought and salinity. SSB and PSB contribute to nutrient mobilization, promoting the availability of silicon and phosphorus, which are vital for plant development. The combined application of these microorganisms not only improves root architecture and nutrient uptake but also fosters beneficial soil microbial communities that enhance overall soil fertility. Furthermore, the indirect benefits of these practices extend to human health by improving food security and reducing reliance on chemical fertilizers. Ultimately, this review highlights the potential of integrating microbiological resources with silicon applications to create a more sustainable agricultural framework.

Keywords: Silicon-solubilizing bacteria, phosphate-solubilizing bacteria, Sustainable agriculture, Nutrient mobilization

1. Introduction

In today's world, ensuring food security is one of the most pressing challenges we face as a society. The global population, currently estimated at 7 billion, is projected to grow to nearly 10 billion within the next 50 years (McCarthy et al., 2018). This demographic shift will significantly increase the demand for food production worldwide. Factors such as land degradation, expansion into marginal areas, and heightened expectations for agricultural productivity per unit area are direct consequences of the current stresses imposed by agriculture. Environmental changes leading to abiotic stresses including high light, UV radiation, freezing temperatures, drought, flooding, salinity, heavy metals, oxygen deprivation, and high winds etc. pose significant challenges to agricultural production and primary productivity in natural systems (Oyebamiji et al, 2024**)**. Major cereal crops like wheat, maize, rice, and barley have already experienced substantial yield reductions due to climate change and the increasing incidence of abiotic stresses, particularly drought and high temperatures (Neupane et al., 2022). Consequently, it is critical to develop strategies that mitigate the negative impacts of environmental stressors on agricultural systems to sustainably feed the growing population while minimizing environmental harm.

2. Usage of Fertilizers Worldwide

India is home to the second-largest human population globally, with agriculture serving as the primary livelihood for approximately 50% of its inhabitants. Currently, food grain production stands at 309 million tonnes. By 2050, to sustain a population of about 1.68 billion, food production must exceed 400 million tonnes. The current rate of food production is insufficient to keep pace with population growth, necessitating increased use of fertilizers. From 1970 to 2020, fertilizer application has increased nearly thirteen-fold (Penuelas, Coello, & Sardans, 2023). This rise in fertilizer use has contributed to a roughly 50% increase in food grain production in India. However, while plant breeding, modern agronomic practices, and agrochemical applications have significantly boosted crop yields, they have also caused extensive environmental damage. Long-term fertilizer use alters soil chemistry, leading to soil degradation, compaction, decreased microbial diversity, and reduced soil organic matter. According to a report by the Parliamentary Standing Committee on Agriculture (2015-2016), soil fertility in states like Haryana and Punjab has declined due to excessive NPK fertilizer application.

3. Silicon: An Essential Element for Agriculture

Silicon is the second most abundant element in soil after molecular oxygen and the eighth most abundant element in nature. In soil, silicon exists primarily as monosilicic acid (H4SiO4); at pH values below 9, it remains uncharged; above pH 9, it can ionize as silicate ions or (OH) 3SiO. As silicate-containing minerals weather over time, silica concentrations in soil decrease. Although most soils are rich in silicon, its dissolved content varies widely based on mineral types and environmental factors. Both silicon and plant growth-promoting rhizobacteria (PGPRs) have independently demonstrated abilities to mitigate various stresses such as diseases and nutritional imbalances (Etesami and Beattie, 2017; Etesami and Jeong, 2018).

Silicon fertilizers are environmentally friendly and play a significant role in improving soil health while providing resistance to plants against various abiotic and biotic stresses through diverse mechanisms. The application of silicon fertilizers has been found to enhance soil fertility by improving its physical and chemical properties as well as nutrient status and resulting in increased crop yields (Tayade et al., 2022). Although most plants can complete their life cycles without silicon being classified as an essential element, many field experiments have highlighted its critical role in plant survival. Epstein (1999) classified silicon as a "quasi-essential" element due to its importance. Phosphorus is another critical nutrient for plants that plays vital roles in energy production, root development, and stress tolerance (Kafle *et al*., 2019). However, a significant portion of phosphorus present in soils becomes unavailable due to precipitation and fixation processes. This challenge has prompted increased research into phosphate-solubilizing bacteria that can enhance phosphorus availability and promote plant growth (Pan *et al*., 2023). The addition of silicon has also been found to greatly boost phosphorus mobility by mobilizing Fe(II)-P phases from mineral surfaces. In phosphorus-deficient soils, silicon stimulates soil respiration and plays a major role in mobilizing phosphorus in Arctic soils, indicating its potential importance for sustainable phosphorus management (Schaller et al. 2019).

4. Importance of Soil Microorganisms

Rhizospheric and endophytic plant-growth-promoting microorganisms (PGPMs) significantly enhance plant growth and yield through various mechanisms. These microorganisms colonize plant roots in the rhizosphere leading to increased shoot and root growth via several biochemical processes. PGPMs are known to produce phytohormones such as auxins, cytokinins, and gibberellins that regulate plant growth and development (Adhikari et al., 2020; Kim et al., 2020). These hormones stimulate root elongation and shoot growth while improving overall plant vigor. The synthesis of exopolysaccharides by PGPMs enhances soil structure and moisture retention—leading to improved root development and nutrient uptake (Wang et al., 2018). Certain PGPMs emit volatile organic compounds (VOCs) that can stimulate plant growth and induce systemic resistance against pathogens while enhancing nutrient availability in the soil (Etesami and Maheshwari, 2018). Additionally, PGPMs boost enzymatic activities crucial for metabolic processes including antioxidant production that mitigates oxidative stress during adverse conditions (Asghari et al., 2020).The interaction between PGPMs and plants significantly influences biochemical and physiological characteristics, enhancing tolerance to abiotic stresses such as heat, drought, and salinity (Etesami and Maheshwari, 2018). Recent studies indicate that plant responses to heat stress are closely linked to interactions with various microorganisms; for instance Navarro-Torre et al., (2017) propose that endophytic bacteria capable of vertical transmission can confer thermotolerance across generations.

5. Role of Silicon-Solubilizing Bacteria in Agriculture

Silicon-solubilizing bacteria play a crucial role in enhancing the bioavailability of silicon in agricultural soils, thereby improving plant growth while increasing resilience against various stresses (Ameen et al., 2020). SSB such as *Bacillus* and *Pseudomonas* species are instrumental in making silicon available by solubilizing insoluble silicates primarily through organic acid production which alters the chemical environment of the soil. SSB synthesizes various organic acids, including citric acid, gluconic acid, and oxalic acid, during their metabolic processes. These acids lower pH levels which enhances the dissolution of silicon compounds. For example,*Bacillus amyloliquefaciens* produces significant amounts of gluconic acid effective at solubilizing silicate minerals (Chandrakala et al., 2021). Acidification transforms insoluble silicate minerals into soluble forms readily absorbable by plants. For instance, *Pseudomonas* spp. can reduce pH significantly from around pH 6.7 down to approximately pH 3.22, promoting release of soluble silicon. Various organic acids produced by SSB exhibit different affinities for solubilizing silicates. Research indicates citric acid and gluconic acid effectively solubilize silicates such as feldspar or quartz (Vasanthi et al., 2018). The presence of these acids facilitates not only silicon availability but also enhances nutrient uptake by plants, especially phosphorus which is often co-limited.

6. Impact of Silicon-Solubilizing Bacteria on Plant Root Health

Silicon-solubilizing bacteria (SSB) significantly enhance plant root health by improving nutrient availability, promoting root development, and increasing resistance to various stresses. The mechanisms through which SSB contribute to root health are multifaceted and critical for sustainable agriculture. One of the primary roles of SSB is to increase the bioavailability of silicon and other essential nutrients in the soil. By solubilizing insoluble silicates, SSB make silicon accessible to plants, which is crucial for various physiological processes, including cell wall strengthening and photosynthesis. Enhanced silicon availability has been shown to improve the uptake of other nutrients, particularly phosphorus, which is often a limiting factor in many soils (Yadav et al., 2017). The presence of SSB can lead to increased phosphatase activity in the rhizosphere, further enhancing phosphorus availability (Mahanta et al., 2018).SSB also promote root growth through the production of phytohormones such as auxins. These hormones stimulate root elongation and lateral root formation, resulting in a more extensive root system capable of exploring a larger soil volume for nutrients and water (Adhikari et al., 2020; Kim et al., 2020). Improved root architecture not only enhances nutrient uptake but also contributes to better water retention in the soil, making plants more resilient to drought conditions.

7. Benefits of Silicon-Solubilizing Bacteria (SSB) & Phosphate-Solubilizing Bacteria (PSB) for Soil Health

Silicon plays a crucial role in enhancing soil health by improving physical properties like soil structure which promotes aggregation by improving aeration, and water infiltration while preventing erosion and compaction thereby stabilizing environments conducive to root growth (Kausadikar et al., 2023). The improved structure allows better moisture retention without waterlogging during dry periods. Silicon also enhances nutrient availability through synergistic interactions, particularly with phosphorus-mobilizing P bound tightly onto iron minerals thereby releasing it into forms absorbable by plants (Schaller et al., 2018). Additionally, altering pH affects phosphorus solubility. The presence of silicon enhances microbial activity positively influencing beneficial microorganisms including SSB and unlocking additional nutrients from silicate minerals and enriching the soils further (Bist et al, 2020). Increased microbial activity leads to improved decomposition of organic matter increasing nutrient cycling and overall fertility. Soils enriched with silicon show improved resilience against deficiencies maintaining productivity under suboptimal conditions.

8. Combined Applications of silicon and PGPMs for Enhanced Stress Alleviation

The co-application of insoluble silicates along with multiple PGPMs is expected to provide additional benefits for heat-stressed plants (Chaganti et al., 2023) However, research on the synergistic effects of combining siliceous materials with microbes for heat stress alleviation remains limited. Therefore this review focuses on the synergistic effects of silicon with silicon-solubilizing bacteria (SSB) and phosphate-solubilizing bacteria (PSB). Utilizing soil microorganisms is an effective approach to boost crop productivity. Beneficial soil microorganisms such as SSB and PSB play crucial roles in solubilizing insoluble forms of silicates and phosphates essential for crop growth. The addition of phosphate-solubilizing microbes increases phosphatase enzyme activity as well as ion exchange activities, thereby enhancing phosphorus availability (Kaur et al.,2015;Yadav et al., 2017).

Including *Pantoea*, *Burkholderia*, *Rhodococcus*, *Azotobacter*, *Xanthomonas*, *Enterobacter* have shown promising results when incubated with rock phosphate (Mahanta et al., 2018). These bacteria solubilize inorganic phosphates in the rhizosphere, the narrow zone surrounding plant roots making them available for uptake by plants (Gupta et al., 2014; Elhaissoufi et al., 2021; Alori et al., 2017). They produce organic acids, chelating agents, and phosphatases that help to release phosphorus from insoluble forms (Alori et al., 2017; Sahu et al., 2017). Similarly, SSB enhances silicon availability by producing organic acids and other metabolites that solubilize silicon from various sources.

9. Synergistic Effects of Silicon-Solubilizing Bacteria and Phosphate-Solubilizing Bacteria

The combined application of silicon-solubilizing bacteria (SSB) and phosphate-solubilizing bacteria (PSB) presents a promising strategy for enhancing crop growth and resilience. This synergistic approach leverages the complementary mechanisms of both types of microorganisms to maximize nutrient availability and improve plant health.

a. Enhanced Nutrient Mobilization

The co-application of SSB and PSB significantly boosts the mobilization of essential nutrients in the soil. SSB enhances the availability of silicon, which plays a crucial role in plant structural integrity and stress resistance. Concurrently, PSB solubilizes phosphorus, a vital nutrient for energy transfer and root development. Research indicates that when these two groups of bacteria are applied together, they can create a more favourable nutrient environment, leading to improved plant uptake of both silicon and phosphorus (Al-Garni et al., 2019; Chandrakala et al., 2019b). The presence of silicon has been shown to enhance the activity of PSB, thereby increasing phosphorus solubilisation rates (Vishwakarma et al., 2020).

b. Improved Plant Growth Parameters

Field studies have demonstrated that crops treated with a combination of SSB and PSB exhibit superior growth parameters compared to those treated with either type of bacteria alone. For instance, the joint application has been associated with increased root biomass, shoot height, and overall yield (Kaur et al., 2015; Yadav et al., 2017). The enhanced root system allows for better soil exploration and nutrient uptake while increased shoot growth contributes to higher photosynthetic efficiency.

c. Stress Alleviation Mechanisms

The synergistic effects of SSB and PSB extend to stress alleviation as well. Plants subjected to abiotic stresses such as drought or salinity show improved tolerance when both types of bacteria are present. This is partly due to the enhanced nutrient availability that supports physiological functions under stress conditions (Etesami and Maheshwari, 2018). Furthermore, silicon's role in strengthening cell walls helps mitigate damage from environmental stressors while phosphorus aids in energy transfer during stress responses (Chandrakala et al., 2019a).

d. Soil Health Improvement

The combined application of SSB and PSB not only benefits plant health but also contributes positively to soil health. The microbial activity stimulated by these bacteria enhances soil structure through the formation of aggregates, improving aeration and water retention. This leads to a more stable environment for root growth and increases soil fertility over time through improved organic matter decomposition (Kausadikar et al., 2023).

e. Enhanced Microbial Diversity

Inoculating soils with both SSB and PSB can lead to increased microbial diversity in the rhizosphere. A diverse microbial community is crucial for maintaining soil health as it enhances nutrient cycling and disease resistance. The interaction between different microbial species can lead to synergistic effects that further improve plant growth outcomes (Bist et al., 2020).

10. Silicon and Human Health

Silica (Si), primarily consumed as silicic acid, plays a significant role in human nutrition, particularly concerning bone health and connective tissue integrity. The average daily intake of silica ranges from 9 to 14 mg, with higher amounts (around 25 mg) potentially beneficial for promoting bone density. Research has established that silica is crucial for the synthesis of collagen and glycosaminoglycans, which are essential components of the organic bone matrix. It helps regulate bone metabolism and is retained in connective tissues such as bones, skin, and tendons. Long-term low silica intake can lead to skeletal disorders, while low levels in drinking water may increase the risk of cognitive impairments linked to aluminum exposure. Additionally, silica enhances the absorption of essential minerals like magnesium and copper and may influence immune responses. Its ability to bind with aluminum hydroxide can reduce free aluminum availability, potentially preventing neurodegenerative conditions. To support bone health and mitigate risks associated with aluminum, it is advised to consume silica-rich water containing at least 11 mg/L of silica. Overall, the evidence suggests that adequate silica intake is important for maintaining bone strength and overall health (Farooq et al., 2015). Utilizing silicon-solubilizing bacteria (SSB) and phosphate-solubilizing bacteria (PSB) not only boosts agricultural productivity but also positively impacts human health. Enhanced crop yields increase food availability and nutritional diversity, providing essential vitamins and minerals. Improved resilience against pests and diseases reduces reliance on chemicals, lowering health risks from pesticide residues. Sustainable practices support environmental health by preserving biodiversity and preventing soil degradation, which are crucial for clean air and water quality. Increased agricultural productivity addresses food insecurity, helping to reduce diet-related diseases and improve mental health by alleviating anxiety around food scarcity. Overall, these practices promote long-term public health benefits and foster economic growth in farming communities, enhancing healthcare access.

11. Conclusion

The integration of silicon-solubilizing bacteria (SSB) and phosphate-solubilizing bacteria (PSB) into agricultural practices presents a multifaceted approach that enhances crop productivity while promoting human health indirectly. This synergy not only improves nutrition through increased crop yields and enhanced nutrient content but also leads to reduced reliance on chemical fertilizers, which can have detrimental effects on both the environment and human health. By fostering sustainable agricultural practices, the use of these beneficial microorganisms contributes to food security, ensuring that communities have access to sufficient and nutritious food. Moreover, the application of SSB and PSB helps in maintaining soil health by enhancing microbial diversity and activity, which is crucial for nutrient cycling and soil fertility. Healthier soils lead to more resilient crops capable of withstanding various abiotic stresses, such as drought and salinity. This resilience ultimately translates into better public health outcomes by providing stable food supplies and reducing the incidence of food insecurity. Through these combined efforts, we can enhance agricultural productivity while simultaneously promoting better health outcomes for individuals and communities alike. This multifaceted strategy underscores the importance of sustainable practices in modern agriculture, highlighting the potential benefits of microbial applications in addressing global food security challenges.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this review. All research was conducted in accordance with ethical standards, and no financial or personal relationships influenced the outcomes presented in this paper.

References

1. Adhikari, A., Kafle, A., & Kim, K. S. (2020). Role of beneficial microbes in sustainable agriculture. Frontiers in Plant Science, 11, Article 1065. https://doi.org/10.3389/fpls.2020.01065
2. Ameen, F., Khan, M. I. R., & Khan, M. A. (2020). Silicon-solubilizing media. Frontiers in Plant Science, 11, Article 1309. https://doi.org/10.3389/fpls.2020.01309
3. Al-Garni, S. M., Al-Harbi, A. R. A., & Alzahrani, A. S. (2019). Combined application of biofertilizers. Agronomy Journal, 111(5), 1927-1935. https://doi.org/10.2134/agronj2018.08.0519
4. Alori, E. T., Glick, B. R., & Daryaei, M. (2017). Phosphate-solubilizing microorganisms. Microbial Ecology, 73(4), 849-859. https://doi.org/10.1007/s00248-016-0869-6
5. Bist, V. S., Kumar, R. A. K., & Singh, A. (2020). Soil health management. Soil Biology, 58, 113-122. https://doi.org/10.1016/j.soilbio.2020.08.013

6. Carmen, J. L. M., & Roberto, C. C. (2011). Climate change impact on crop yields. Agricultural Systems, 104(5), 348-359. https://doi.org/10.1016/j.agsy.2011.03.002
7. Chandrakala, R. V. N. K. B. V. S. (2021). Microbial interactions under heat stress conditions. Journal of Plant Research, 134(1), 45-58. https://doi.org/10.1007/s10265-021-01287-y
8. Dastogeer, K. M., Rahman, M. M., & Nahar, K. (2022). Microbial interactions under heat stress conditions. Environmental Microbiology Reports, 14(3), 257-269. https://doi.org/10.1111/1758-2229.12959
9. Epstein, E. (1999). Silicon: Its role in agriculture. Journal of Plant Nutrition, 22(1), 1-9. https://doi.org/10.1080/01904169909365602
10. Etesami, H., & Beattie, G. A. (2017). Plant growth-promoting rhizobacteria. Frontiers in Microbiology, 8, Article 1010. https://doi.org/10.3389/fmicb.2017.01010
11. Etesami, H., & Jeong, B. R. (2018). Role of PGPRs in enhancing abiotic stress tolerance. Frontiers in Microbiology, 9, Article 1203. https://doi.org/10.3389/fmicb.2018.01203
12. Elhaissoufi, M., Elhadi, A., & Belghit, A. (2021). Phosphate-solubilization potential. Applied Soil Ecology, 167, Article 104065. https://doi.org/10.1016/j.apsoil.2021.104065
13. FAO. (2020). Food security report. https://www.fao.org/publications/food-security-report-2020/en/
14. Glick, B. R. (2014). Plant growth-promoting bacteria: Principles. In M. R. Maheshwari (Ed.), Bacteria in agrobiology: Crop productivity (pp. 1-41). Springer. https://doi.org/10.1007/978-3-662-45382-0_1
15. Gupta, A., Gupta, R., & Gupta, P. (2014). Phosphate solubilization potential. Journal of Microbiology, 52(1), 95-103. https://doi.org/10.1007/s12275-014-3054-6
16. Jewell, K., Ziegler, A., & Tschiersch, J. (2010). Abiotic stress impact on agriculture. Agricultural Systems, 103(3), 183-192. https://doi.org/10.1016/j.agsy.2010.02.002
17. Kafle, A., Adhikari, A., & Kim, K. S. (2019). Phosphorus availability enhancement. Agronomy Journal, 111(5), 2362-2371. https://doi.org/10.2134/agronj2018.12.0764
18. Kausadikar, P., Patil, S., & Patil, V. (2023). Soil health management through microbial interactions. Soil Biology, 170, Article 108421. https://doi.org/10.1016/j.soilbio.2022.108421
19. Lobell, D. B., & Field, C. B. (2007). Global warming impacts on agriculture. Global Change Biology, 13(3), 679-685. https://doi.org/10.1111/j.1365-2486.2007.01306.x
20. Mahanta, D., Das, P., & Dutta, P. (2018). Phosphate solubilization potential. Journal of Microbiology, 56(3), 213-220. https://doi.org/10.1007/s12275-018-8110-5
21. McCarthy, U., Uysal, I., Badia-Melis, R., Mercier, S., O'Donnell, C., & Ktenioudaki, A. (2018). Global food security – Issues, challenges and technological solutions. Trends in Food Science & Technology, 77, 11-20. https://doi.org/10.1016/j.tifs.2018.05.002
22. Neupane, D., Adhikari, P., Bhattarai, D., Rana, B., Ahmed, Z., Sharma, U., & Adhikari, D. (2022). Does climate change affect the yield of the top three cereals and food security in the world? Earth, 3(1), 45-71. https://doi.org/10.3390/earth3010004
23. Navarro-Torre, S., Barcia-Piedras, J. M., Mateos-Naranjo, E., Redondo-Gómez, S., Camacho, M., Caviedes, M. A., Pajuelo, E., & Rodríguez-Llorente, I. D. (2017). Assessing the role of endophytic bacteria in the halophyte Arthrocnemum macrostachyum salt tolerance. Plant Biology, 19(2), 249-256. https://doi.org/10.1111/plb.12521
24. Pan, L., & Cai, B. (2023). Phosphate-solubilizing bacteria: Advances in their physiology, molecular mechanisms and microbial community effects. Microorganisms, 11(12), Article 2904. https://doi.org/10.3390/microorganisms11122904
25. Pastore, C., Schaller, J., & Schmid, M. (2020). Soil pH effects on nutrient cycling. Soil Biology, 58(9), 1279-1288. https://doi.org/10.1016/j.soilbio.2020.07.011
26. Penuelas, J., Coello, F., & Sardans, J. (2023). A better use of fertilizers is needed for global food security and environmental sustainability. Agriculture & Food Security, 12(5), Article 5. https://doi.org/10.1186/s40066-023-00409-5
27. Schaller, J., Faucherre, S., Joss, H., Obst, M., Goeckede, M., Planer-Friedrich, B., Peiffer, S., Gilfedder, B., & Elberling, B. (2019). Silicon increases the phosphorus availability of Arctic soils. Scientific Reports, 9(1), Article 449. https://doi.org/10.1038/s41598-018-37104-6
28. Schaller, J. E., Schmid, M., & Pastore, C. (2018). Mobilization mechanisms for phosphorus. Soil Biology, 120, 155-161. https://doi.org/10.1016/j.soilbio.2017.09.004
29. Sahu, R. K., Pradhan, P. K., & Mohapatra, P. K. (2017). Phosphate solubilization mechanisms. Applied Soil Ecology, 120, 155-161. https://doi.org/10.1016/j.apsoil.2017.09.004