UNLOCKING THE POTENTIAL OF SILICATE SOLUBILIZING BACTERIA FOR ENHANCED CROP GROWTH AND ENVIRONMENTAL SUSTAINABILITY

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Silicate solubilizing bacteria (SSB) are essential microbes that play an important role in the biogeochemical cycle of silicon (Si) in the environment. These remarkable organisms possess the ability to dissolve silicate minerals into forms that are readily available to plants. This process not only increases plant-accessible silicon but also promotes growth and enhances resistance to various stresses. Besides, SSBs help to unlock essential nutrients like phosphorus and potassium, making them valuable contributors to soil fertility and enhanced plant defence mechanisms.

CHARACTERIZATION & ISOLATION OF SSB

The significance of soil microbes in nutrient availability and weathering of primary minerals, and Si-solubilizing abilities with different sources and species of bacteria used in the isolation and characterization of SSBs are presented in Table 1. The rhizosphere, teeming with life, is a hotspot for silicate interaction. Microbial metabolites, hand-in-hand with plant root exudates, work their magic on silicate minerals through various mechanisms. Some alter the surrounding environment by shifting redox conditions, while others acidify it or chelate nutrients, effectively unlocking secrets from these complex structures. While the exact process of Si release from silicate minerals by microorganisms, particularly SSBs, remains a mystery as some pieces of information are still missing, several strategies are known to be employed to understand the Sil release mechanism. These clever microbes utilize a diverse toolbox, including ligands, acids, alkalis, and even extracellular polysaccharides. Jongsmans et al. (1997) reported that acidolysis i.e., the breakdown of minerals by acidic substances, reigns supreme as the most common method for silicate mineral weathering.

The ability of SSBs to unlock the secrets of Si largely hinges on their production of tiny organic acids. These acids behave like microscopic pickaxes, chipping away at the walls of complex silicate minerals. Gluconic, acetic, and formic acids are some of the most common tools in their arsenal, particularly effective against stubborn tri-calcium silicates and other hidden nutrients. These acids work their magic by targeting the silicon-oxygen bond (O-Si-O) in quartz, like skilled locksmiths cracking a code. The process releases tiny warriors known as protons (H^+), which further weaken the mineral defences. When the pH is just right, and there are enough positively charged ions (cations) and hydroxide ions (OH^-) around, weak organic acids like carboxylates get activated, like soldiers charging into battle. This combined attack ultimately leads to the breakdown of the mineral, releasing plant-friendly monosilicic acid, making silicon readily available for plant growth (Ma and Naoki, 2015).

Bist et al. (2020) has revealed a fascinating connection between how bacteria unlock silicon (Si), the activity of acidic phosphates, and the production of various organic acids like gluconic and succinic. It turns out, there are two main ways this 'dissolving act' happens- (i) through the pH plunge - here, when the pH drops, it weakens the bonds holding Si captive and this 'proton-promoted dissolution' process is like using a tiny army of protons to break down mineral's defences (Pastore et al., 2020); (ii) other one is through the acidic grip - microbes can release special organic acids that act like molecular claws, grabbing onto the mineral and prying the silicon loose. This 'ligand-promoted dissolution' shows why sometimes, a lower pH isn't as crucial.

Experiments with various materials like diatomite and quartz revealed that the biggest pH drops occur when dealing with tougher opponents like aluminosilicates. Here, both 'pH changes' and the 'acidic grip' work together to break down the strong Al-O-Si and Mg/Ca-O-Si bonds. However, for simpler materials like plant husks and straw, where silicon is more loosely bound, the organic acids often take center stage. They weaken the Si-O-Si bonds like skilled locksmiths, freeing the silicon without needing a major pH drop.

Table 1. Sources of SSB, along with the bacterial species involved, and the media used for their isolation and characterization

ISOLATE FROM	CROP	BACTERIA	MEDIUM USED	CITATION
Rice field	*Oryza sativa* L. cv. Dongjin	*Burkholderia eburnea*	Silicate medium containing magnesium silicate	Kang *et al*., 2017
Earthworm guts and surrounding soil	Maize	*Aeromonas, Bacillus, Flavobacterium, Microbacterium, Paracoccus, Cellvibrio, Ensifer, Pseudomonas, Rhizobium,* and *Streptomyces*	Aleksandrov's medium containing $KAlSi_3O_8$	Hu *et al*., 2018
Rhizosphere soil	Rice	*Rhizobium* sp.	Bunt and Rovira medium containing magnesium trisilicate	Chandrakala *et al*., 2019
Rhizosphere soil	Paddy	*Enterobacter ludwigii*	Glucose agar medium containing magnesium trisilicate	Lee *et al*., 2019
Clay substrate	Mustard	*Bacillus* sp.	Zak–Alexandrov medium containing Na_2SiO_3	Maleva *et al*., 2017
Different location and rhizosphere	Rice	*Pseudomonas* and *Bacillus (Sphingobacterium* sp., *B. amyloliquefaciens)*	Silicon solubilizing media (NBRISSM) containing feldspar as silicate	Bist et al., 2020

IMPORTANCE OF SSB IN SUSTAINABLE AGRICULTURE

Plant Growth Powerhouses: Imagine tiny bacteria acting like nature's secret weapon, unlocking essential silicon from minerals and boosting plant growth, yield, and quality. These microbes not only make Si more accessible to plants, but they also offer several other benefits. Bacteria *like Bacillus amyloliquifaciens*, known for its silicon-unlocking abilities, can also act as warriors against harmful fungi like *Rhizoctonia solani*, the culprit behind sheath blight disease (Bist et al., 2020). *Enterobacter ludwigii*, another champion of Si and phosphorus solubilization, produces a cocktail of beneficial acids and hormones (citric, acetic, lactic, indole-3-acetic, and gibberellic acid). This potent mix helps rice seeds germinate better, grow stronger, and even pack a punch of chlorophyll (Lee et al., 2019).

Studies of Maleva et al. (2017) showed biofertilizers containing SSBs, when applied to clay-rich soils, improved structure and function of leaves in *Brassica juncea*, leading to better CO_2 absorption. This means more efficiency in photosynthesis and potentially higher yields.

Strategic use of SSBs, particularly in combination with fly ash and farmyard manure, has been shown to have significant effect on increasing grain yield and enhancing the overall sugarcane production, both in the initial harvest and subsequent ones. Figure 1 depicts a view of the experimental fields of Si fertilization at ICAR-IISS Bhopal.

Soil Health: SSBs play a crucial role in enhancing soil structure. They act like tiny architects, helping to create a more stable and well-aggregated soil. This improved structure allows for better water infiltration, drainage, and oxygen availability, all essential for healthy plant growth. SSBs help in boosting the soil fertility through converting insoluble forms of plant nutrients like silicon, potassium, and zinc to available forms, which makes them readily accessible to plants and ultimately lead to increased plant productivity (Maleva et al., 2017). Also, they promote growth of other beneficial microorganisms in the soil. This diverse microbial community plays a vital role in maintaining a healthy and balanced soil ecosystem, further supporting plant growth and overall soil health. The benefits of SSBs extend beyond just the major nutrients. Studies have shown that SSBs not only facilitate the release of phosphorus and potassium, but also improve the uptake of micronutrients like iron and manganese by plants (Kausadikar et al., 2019).

Figure 1. A view of experimental at fields of ICAR-IISS Bhopal **(a)** foliar application of Si **(b)** assessment of physiological parameters using portable photosynthesis system GFS 3000

UNVEILING THE POTENTIAL OF SSB

Researchers around the world are actively exploring the fascinating world of SSBs. Efforts are going on to identify potent SSB strains that can outperform existing ones and unravel the intricate mechanisms behind SSB's beneficial actions as it is crucial for optimizing their use. Since SSB can also act a green alternative, one of the most exciting areas of investigation is the use of SSB as biofertilizers. This offers a sustainable alternative to conventional soil amendments, reducing reliance on harmful chemicals in farming and promoting eco-friendly practices.

Application of SSB biofertilizers can be done through several ways viz., seed treatment (smearing of biofertilizer@10g/ kg seed before sowing), seedling dip (dip seedlings in biofertilizer solution for 30 minutes before transplanting), and direct application (to soil @ 3-5 kg/acre) and drip irrigation (with irrigation water @ 3 kg/acre). A tailored approach is crucial to maximize the benefits of SSB. By understanding the research landscape and various application methods, we can unlock the full potential of these tiny but powerful soil superheroes.

CONCLUSION

Silicate-solubilizing bacteria (SSB) are no longer hidden figures in the soil but, emerging as game-changers in the realm of sustainable agriculture and environmental management. Their unique ability to unlock Si from minerals has far-reaching benefits. Improved Si uptake translates to stronger, more disease-resistant plants, leading to increased crop yields. SSB act as tiny soil architects by enhancing structure and promoting the availability of essential nutrients to plants, and creating a richer and more productive environment for plant growth. In this way, SSB contribute to a healthier and more balanced ecosystem. Thus, incorporating SSB into integrated soil and crop management strategies holds immense potential. With continued research, these environmental champions can be utilized more effectively in building a more sustainable future for agriculture and the environment.

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