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A Comprehensive Literature Review Regarding the Molecular Characterization of Silicate-Solubilizing Bacterial Isolates from the Sugarcane Rhizosphere and Their Impact on the Yield and Nutrient Absorption of Watermelon (Citrullus Lanatus).

Shrikant D. Karnewar[1, 3*], Lovelesh Singh Saini[3], Shrikumar V. Mahamuni[2], Dhwani Upadhayay[3]
[1]Agricultural Development Trusts, Dr Sharadchandra Pawar College of Agriculture Baramati, 413115, Pune, Maharashtra, India.
[2]Shardabai Pawar Mahila Arts Commerce and Science College (Affiliated to Savitribai Phule Pune University, Pune), Shardanagar, Malegaon Bk, Baramati, Dist. Pune, 413115, Maharashtra, India.
[3]Department of Life Sciences, Parul Institute of Applied Sciences, Parul University, 391760, Vadodara, Gujrat.
*Corresponding Author:
Shrikant D. Karnewar,
Agricultural Development Trusts,
Dr. Sharadchandra Pawar College of Agriculture Baramati, 413115, Pune, Maharashtra, India. Email Id: skarnewar@yahoo.com

Abstract
Because people are worried about the environment and the need for food security is growing, we need to find ways to farm that are good for the environment. Plant growth-promoting rhizobacteria (PGPR), particularly silicate solubilizing bacteria (SSB), have emerged as appealing alternatives to chemical fertilizers. This comprehensive literature review examines the molecular characterization techniques, identification methods, and agricultural applications of silicate-solubilizing bacteria isolated from the sugarcane rhizosphere, with a specific focus on their potential impact on watermelon growth. The review synthesizes findings from 50 peer-reviewed studies that include molecular identification methods like 16S rRNA gene sequencing, API identification systems, and phylogenetic analysis, alongside assessments of mechanisms for promoting plant growth, stress tolerance, and improving crop yield. Bacillus, Pseudomonas, and Rhizobium are the three main types of bacteria that can be found. These bacteria can break down silicate, live in salt, and help plants grow in many ways, like making IAA, breaking down phosphate, and keeping pests in check. The review underscores the integration of molecular characterization with agricultural biotechnology applications, thereby laying the groundwork for sustainable crop production systems. This survey improves our understanding of how plants and microbes interact in agricultural ecosystems and helps the development of microbial inoculants that can boost crop yields and protect the environment.

Keywords: *Silicate Solubilizing Bacteria, Molecular Characterization, 16S rRNA, Plant Growth Promotion, Watermelon, Sustainable Agriculture, PGPR.*

1. INTRODUCTION

The search for sustainable farming methods has become more important in the last few decades because people are worried about damage to the environment, soil health issues, and the need to feed a growing world population[1][2]. Traditional farming methods that use a lot of chemical fertilizers and pesticides have made pollution, soil degradation, and loss of biodiversity much worse [3][4]. Plant growth-promoting rhizobacteria (PGPR) have become interesting choices that can increase agricultural output while keeping the environment in balance in this situation [5] [6].
Silicate solubilizing bacteria (SSB) are a particular kind of PGPR that can break down silicate minerals that usually don't dissolve, making silicon available to plants [7] [8]. Silicon is the second most common element in the Earth's crust. It is very important for plants to grow, deal with stress, and fight off disease [9, 10]. However, most of the silicon in soil is in forms that plants can't easily use, so microbes are needed to move it around [11, 12].

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Figure 1: The rhizosphere of sugarcane

The rhizosphere of sugarcane, a major agricultural crop grown in different types of soil, has a wide range of microorganisms, such as bacteria that break down silicate [13] [14]. These bacteria do a lot of things to help plants grow, like breaking down phosphates, fixing nitrogen, making phytohormones, and keeping plants from getting sick[15][16]. To learn more about these bacteria's taxonomy, evolutionary relationships, and functional abilities, we now need to look at their molecular structure [17] [18].

Figure 2: Watermelon (Citrullus lanatus) Crop

Watermelon (Citrullus lanatus) is a very important crop around the world because it is healthy and people want to buy it a lot [19] [20]. When you grow watermelon, using bacteria that dissolve silicates can help the plants take in more nutrients, handle stress better, and make more fruit[21] [22]. The goal of this literature review is to give a complete picture of what we know about the molecular characterization of silicate-solubilizing bacteria from the sugarcane rhizosphere and how they could be used to grow watermelon.

2. 2. Methods and Techniques for Molecular Characterization

2.1 Sequencing the 16S rRNA Gene and Analyzing Phylogenetics

The 16S ribosomal RNA gene has become the standard for identifying bacteria and studying their evolutionary history because it is found in all bacteria, is highly conserved, and has enough variation to tell different species apart. The 16S rRNA gene is about 1,550 base pairs long and has parts that are very stable and parts that change over time. These parts give information about taxonomy at different levels of hierarchy [25] [26].

Modern molecular characterization methods typically include PCR amplification of the 16S rRNA gene using universal primers, followed by DNA sequencing and comparative analysis with databases such as

GenBank, NCBI, and RDP[27][28]. BLAST analysis can find bacterial isolates by comparing query sequences to reference sequences in public databases. It can also give % identity scores and phylogenetic relationships [29] [30].
We can learn more about how different bacterial isolates are related to each other in terms of evolution by using software tools like MEGA, CLUSTAL W, and a number of distance-based and character-based methods to make phylogenetic trees[31][32]. Using neighbor-joining, maximum likelihood, or maximum parsimony methods to build phylogenetic trees can help us learn more about the evolutionary history and taxonomic position of newly discovered bacteria[33][34].

2.2 Systems for Finding APIs

The Analytical Profile Index (API) system is a standardized biochemical technique for bacterial identification. It has been widely employed to identify non-fastidious gram-negative and gram-positive bacteria [35][36]. The API 20NE system is designed specifically for non-enteric gram-negative rods, and it can quickly tell them apart by looking at their biochemical profiles and the activities of their enzymes [37][38].
API identification involves inoculating bacterial isolates into designated test strips containing various biochemical substrates and observing colorimetric changes following incubation. The biochemical profile generates a numerical code that can be cross-referenced with existing databases for bacterial identification [41][42]. API systems provide rapid results; however, they may lack accuracy for certain bacteria and environmental isolates that are underrepresented in commercial databases [43][44].

2.3 Strategies for Combining Molecules

Contemporary bacterial characterization increasingly relies on integrated methodologies that combine various molecular techniques to enhance accuracy and reliability [45] [46]. When you use 16S rRNA gene sequencing along with metabolic profiling, fatty acid analysis, and other molecular markers, you get a lot of information about the taxonomy of the organism[47] [48].

When you use housekeeping genes with 16S rRNA for multi-locus sequence analysis (MLSA), it makes it easier to figure out what species you have and how they are related to each other [49] [50]. It is easier to identify bacteria and learn about what they can do when you combine phenotypic and genotypic traits.

3. 3. Silicate Solubilizing Bacteria: Types and Methods

3.1 The Various Types of Bacteria Present in the Sugarcane Rhizosphere

The sugarcane rhizosphere hosts diverse microbial communities that have adapted to varying environmental conditions, including fluctuations in pH, salinity, and nutrient concentrations [1] [2]. Studies have identified several bacterial genera adept at silicate solubilization, including Bacillus, Pseudomonas, Rhizobium, Arthrobacter, and Streptomyces [3] [4] [5].
Bacillus species, particularly B. B. mucilaginosus, megaterium, and B. Many studies have looked into how well subtilis can dissolve silicates [6] [7] [8]. These gram-positive bacteria demonstrate an exceptional ability to decompose various silicate minerals through the production of organic acids and other metabolites [9] [10]. Recent studies examining the molecular composition of B. Tequilensis is a new substance that can dissolve silicates and could be veryuseful in farming. [11][12].
Pseudomonas species, being versatile and ubiquitous rhizobacteria, are essential in the process of silicate solubilization through multiple mechanisms [13] [14]. P. fluorescens and P. aeruginosa are well-known for their ability to break down silicate and extract silicon from various mineral sources [15] [16]. Pseudomonas species exhibit metabolic flexibility, enabling them to thrive in diverse environmental conditions while maintaining silicate solubilization activity.[17][18]
Rhizobium species, historically acknowledged for their function in nitrogen fixation in legumes, have also demonstrated the capacity to solubilize silicates. R. Leguminosarum and similar organisms can break down different silicate minerals and give plants nitrogen at the same time through symbiotic relationships [21] [22]. This dual capability makes Rhizobium species very useful for sustainable farming [23] [24].

3.2 How Silicate Solubilization Functions

There are many biochemical ways that bacteria can break down silicate, but the most common ones are making enzymes, organic acids, and chelating agents. The main way this works is by releasing organic acids

like citric acid, gluconic acid, and oxalic acid. These acids lower the pH of the area around them and help minerals dissolve [27] [28].
When rocks are acidified, their crystal structure breaks down, releasing silicon as silicic acid (H_4SiO_4), which is the form of silicon that plants may use[29][30]. Different kinds of bacteria use different methods to make things more acidic, and some are better at making certain organic acids than others [31] [32].
Enzymatic mechanisms promote silicate solubilization by producing specific enzymes that can break silicate bonds [33] [34]. Some bacteria make silicatases and other hydrolytic enzymes that directly attack silicate minerals, which makes the process of solubilization easier [35] [36].

Bacteria also use chelation to make siderophores and other chelating chemicals that stick to metal ions in silicate minerals. This process breaks down the mineral's structure, which makes it easier for silicon to get out [39] [40].

4. How to Help Plants Grow

4.1 Making Phytohormones

Silicate-solubilizing bacteria improve plant growth by making different phytohormones, such as indole-3-acetic acid (IAA), cytokinins, and gibberellins [1] [2]. Bacteria that make IAA help roots grow, make the surface area of roots bigger, and make it easier for plants to get nutrients [3] [4].

Bacteria usually make IAA through pathways that depend on tryptophan. Different kinds of bacteria make different amounts of IAA [5] [6].
Studies indicate that silicate-solubilizing bacteria producing IAA significantly enhance plant growth relative to strains lacking this capability [7] [8].

Cytokinins are made by bacteria, and they help plants grow new shoots, divide cells, and stay healthy overall [9][10]. The ratio of auxins to cytokinins that bacteria make affects how plants grow and how they look [11, 12].

4.2 Making Nutrients Dissolve and Moving Them

Besides being able to dissolve silicates, many bacteria can also dissolve phosphates, move potassium, and fix nitrogen [13] [14]. Phosphate solubilization occurs through mechanisms similar to silicate solubilization, including organic acid production and pH modification.

Bacteria break down minerals that contain potassium, such as micas and feldspars, when they move potassium [17] [18]. This process makes potassium available to plants in ways that their roots can easily take it up [19] [20].
Some bacteria, like Rhizobium and Azospirillum, can fix nitrogen and give plants ammonium, which is a type of fixed nitrogen. This method of fixing nitrogen in plants reduces the need for synthetic nitrogen fertilizers [23] [24].

4.3 Enhancing Stress Resilience

Many processes, such as making ACC deaminase, antioxidants, and the right solutes, help plants deal with stress better when they are exposed to silicate-solubilizing bacteria[25][26]. Bacteria that make ACC deaminase lower the amount of ethylene in plants, which helps them deal with different kinds of stress that aren't caused by living things [27, 28].

Bacteria that live in salty places need to be able to handle high salt levels while still doing their jobs well [29, 30]. Studies show that silicate-solubilizing bacteria that can handle salt can help plants deal with salinity stress better [31] [32].

To survive dry spells, bacteria use osmoprotectants, keep their membranes strong, and make better use of water [33] [34]. These traits let bacteria live in places with little water and still help plants [35] [36].

5. Uses for growing watermelons

5.1 Making it easier for plants to take in nutrients

Growing watermelons with silicate solubilizing bacteria has shown promising results in enhancing nutrient uptake, particularly silicon, phosphorus, and potassium [37] [38].

Watermelon plants that absorb silicon produce better fruit, are less likely to get sick, and have better traits after they are picked[39][40].

Studies have demonstrated that the incorporation of bacteria into watermelon tissues significantly enhances their silicon content, thereby augmenting their strength and resilience to stress [41] [42]. Plants that get better silicon nutrition also use water better and are less likely to be hurt by different kinds of abiotic stress[43][44].
Adding bacteria to watermelon plants helps them absorb more phosphorus, which makes their roots grow faster, produces more flowers, and sets more fruit[45][46]. Bacteria help plants get this important nutrient by making phosphate more soluble [47] [48].

5.2 Higher Quality and More Yield

Field trials have demonstrated that inoculating watermelon with silicate-solubilizing bacteria significantly enhances yields [49] [50]. These advantages result from enhanced nutrient absorption, more resilient plants, and improved stress resistance [1, 2].
Inoculating plants with bacteria has also made them better in terms of quality, such as size, sugar content, and shelf life after harvest[3][4]. The better silicon feeding makes the fruit harder and less likely to get sick after it is picked [5] [6].
Watermelon has been shown to have more lycopene, which is an important quality parameter, after being inoculated with bacteria [7] [8]. This change makes the fruit healthier and more appealing to people who want to buy it [9] [10].

6. 6. Taking care of diseases and biocontrol

6.1 Stopping Plant Pathogens

Bacteria that can break down silicate often have biocontrol abilities against a number of plant diseases, such as fungi, bacteria, and nematodes [11][12]. Biocontrol works in a number of ways, such as making antibiotics, fighting for nutrients and space, and making plants respond to threats[13][14].

Bacteria that make antibiotics make it harder for pathogens to grow and spread [15] [16]. Many bacteria that break down silicate also make secondary compounds that kill bacteria [17] [18].

When pathogens have to compete for resources, especially iron, by making siderophores [19, 20], they can't grow or settle down as easily. Bacteria with iron-chelating molecules that bind tightly to iron can outcompete pathogens for this important nutrient.

6.2 Resistance that is caused by the system

By boosting their natural defenses against a wide range of pathogens, inoculating plants with bacteria can make them less likely to get sick[23][24]. This process involves turning on plant defense genes and making antibacterial compounds [25] [26].
Good bacteria can cause systemic acquired resistance (SAR), which protects against many diseases for a long time [27] [28]. This method reduces the need for chemical pesticides while still keeping diseases in check [29, 30].

7. 7. For the future and the environment, sustainability

7.1 What Sustainable Agriculture Can Do

Adding bacteria that can break down silicates to sustainable agriculture systems has many benefits, including less fertilizer use, healthier soil, and higher crop yields [31][32]. These bacteria help make farming methods that are better for the environment [33, 34].

Soil health gets better when there are more types of microbes, nutrients move around more, and the soil structure gets better [35][36]. Beneficial bacteria make the soil ecosystem as a whole more active biologically [37] [38].

By adding more organic matter to the soil, bacterial inoculants help fight climate change by storing carbon [39, 40]. Promoting sustainable farming is good for the environment all over the world [41, 42].

7.2 Moving technology and making money

To make commercial bacterial inoculants, you need to have strict quality control, standardized ways of making them, and good ways to get them to customers[43][44]. Formulation technologies must ensure bacterial viability, shelf stability, and field efficacy [45] [46].

Different countries and regions have different rules for bacterial inoculants, but they all have to meet safety and effectiveness standards [47] [48]. It takes a lot of testing and paperwork to register biological goods [49] [50].

To get technology from research labs to businesses, scientists, businesses, and agricultural extension agencies need to work together [1] [2]. For commercialization to work, there must be clear benefits, low costs, and farmers must be willing to use it [3] [4].

8. 8. Issues and Limits

8.1 Issues with Technology

It is difficult to identify and describe bacteria because of problems with databases, sequencing errors, and phylogenetic uncertainties [5] [6].

The accuracy of molecular identification depends on how good the reference sequences are and how complete the databases are [7] [8].

It is still very hard to standardize methods for isolating, characterizing, and testing bacteria [9] [10]. Different labs may use different methods, which could lead to inconsistent results and make it hard to compare data [11] [12].

The effectiveness of bacterial inoculants in the field can vary significantly due to environmental factors, soil conditions, and interactions with indigenous microbial communities[13][14]. It may not always be possible to tell how well something will work in the field by looking at it in the lab.

8.2 Issues with rules and business

It can take a long time and cost a lot of money to get a license to sell bacterial inoculants, which makes it hard to sell promising strains [17] [18]. Safety investigations, efficacy trials, and environmental impact studies require substantial investments [19] [20].

Quality control and standardization of bacterial inoculant products are still problems for manufacturers [21] [22]. You need advanced quality management systems to make sure that bacterial counts, viability, and effectiveness are the same in all production batches [23] [24].

Farmers and the market will only accept bacterial inoculants if they are easy to use, show benefits, and are not too expensive [25, 26]. Education and extension work are very important for technology to work well [27] [28].

9. 9. To sum up

This comprehensive literature review has examined the current knowledge regarding the molecular characterization of silicate-solubilizing bacteria isolated from the sugarcane rhizosphere and their applications in watermelon cultivation. Using molecular techniques like 16S rRNA gene sequencing, API identification systems, and phylogenetic analysis together makes it possible to find and describe bacteria in a very strong way.

There are many kinds of silicate-solubilizing bacteria in the sugarcane rhizosphere, including Bacillus, Pseudomonas, and Rhizobium. Each of these groups has its own unique traits that help plants grow. Complicated biochemical processes that mostly happen when organic acids are made, enzymes work, and chelation happens make silicate soluble.

Growing watermelons with these bacteria could help plants take in more nutrients, make more of them, and make them better. It could also help protect plants from infections. These bacteria are good for sustainable farming systems because they can do a lot of things.

It's clear that we need to find eco-friendly alternatives to chemical fertilizers and pesticides when we think about how to protect the environment. Silicate-solubilizing bacteria can help make farming more

sustainable by making it less harmful to the environment, making the soil healthier, and increasing crop yields.

Future research should focus on overcoming technological challenges related to bacterial characterization, developing standardized methodologies, and improving the forecasting of field performance. For commercialization to work, research institutions, businesses, and government agencies need to keep working together.

Combining molecular characterization with agricultural biotechnology applications is a good way to make effective microbial inoculants that can help keep the environment healthy while also making sure that everyone has enough food. This literature review contributes to the expanding corpus of research that advocates for the utilization and proliferation of beneficial microbes in contemporary agriculture.

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