Journal of Agriculture and Veterinary Science
ISSN: 2959-1198 (Print), 2959-1201 (Online)

Review Article

Investigating the Role of Solubilizing Bacteria in the Phosphorus Cycling and Organic Matter Dynamics

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ABSTRACT

In alkaline calcareous soils, where phosphorus is usually immobile and unavailable for plant uptake, phosphorus solubilizing bacteria (PSB) are essential for increasing the bioavailability of phosphorus in soils. Through the synthesis of organic acids and other processes, these bacteria solubilize inorganic phosphate compounds, greatly enhancing the cycling of phosphorus. The purpose of this review is to explore how PSB enhances phosphorus availability and how it interacts with the dynamics of organic matter in alkaline calcareous soils, which are common in many arid and semi-arid regions. Important findings from the literature show that PSB interact with organic matter to improve soil fertility overall in addition to increasing phosphorus availability. Research have indicated that temperature, pH, and inputs of organic carbon all affect PSB activity. The review also emphasizes the challenges presented by environmental factors that limit bacterial efficaciousness in phosphorus solubilization, as well as the symbiotic relationship between PSB and other soil microorganisms. This review has significant outcome for environmentally friendly farming. Growers can encourage more economical and environmentally friendly farming practices by lowering their reliance on chemical phosphorus fertilizers by using PSB as biofertilizers. By promoting nutrient cycling, accelerating the breakdown of organic matter, and possibly raising carbon sequestration, PSB activity also contributes to the long-term health of the soil. For sustainable agricultural productivity and environmental conservation, this research emphasizes the significance of microbial interventions in managing nutrient-deficient soils.

Keywords: Phosphorus, PSB, Organic Matter, Soils.

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Article History
Received: June 11, 2024
Accepted: August 28, 2024
Published: August 30, 2024

INTRODUCTION

Background on Phosphorus in Soils

One essential nutrient that is essential to the growth, development, and reproduction of plants is phosphorus (P). It has a role in several important physiological functions, including nucleic acid synthesis, photosynthesis, and energy transfer.

The availability of phosphorus is crucial to agriculture because a shortage of the mineral in the soil can drastically reduce crop productivity (Raghothama, 1999). To meet crop needs, phosphorus is typically applied in the form of chemical fertilizers in agricultural systems. But only a small portion of the phosphorus that is applied reaches the plants; the remainder is fixed in soil particles, especially in soils that have a high calcium content (Holford, 1997). A significant obstacle to sustainable agriculture is the immobility of phosphorus in soils and its low bioavailability, which results in excessive fertilizer use, environmental damage, and financial hardship for farmers (Schröder et al., 2011). Strategies to increase soil phosphorus use efficiency are becoming more and more important in the context of global food security and environmental sustainability. Increasing the availability of phosphorus biologically for example, by using soil microbes has shown to be a viable approach. Microorganisms, particularly bacteria that solubilize phosphorus, possess the ability to release phosphorus that is confined in soil particles, thereby increasing its availability to plants (Rodríguez and Fraga, 1999).

Alkaline calcareous soils and phosphorus availability

Alkaline calcareous soils are distinguished by a high calcium carbonate content and a pH of over 7.5. Due to phosphorus's strong binding to calcium ions, which results in the formation of insoluble calcium-phosphate compounds, these soils which are typical in arid and semi-arid regions pose special difficulties for phosphorus availability (Bechtaoui et al., 2021). As a result, no matter how much phosphorus fertilizer is used, phosphorus becomes largely unavailable to plants. The phosphorus shortage in these soils is further exacerbated by the high pH, which also prevents phosphate minerals from dissolving (Brownrigg et al., 2022).

Because of the interactions between phosphorus, calcium, and soil organic matter, the nutrient dynamics in alkaline calcareous soils are very different from those in other soil types. These soils also have slower organic matter decomposition, which has an indirect effect on phosphorus cycling by lowering the release of phosphorus that is bound to organic matter. Finding effective ways to increase phosphorus availability in such difficult soil environments is essential for increasing crop productivity, given the critical role phosphorus plays in plant growth.

Role of solubilizing bacteria in phosphorus cycling

The capacity of phosphorus solubilizing bacteria (PSB) to change insoluble forms of phosphorus into bioavailable forms that are easily absorbed by plant roots has drawn attention to PSB. PSB accomplish this through a variety of methods, the most popular being the secretion of organic acids that dissolve phosphate minerals, such as citric, lactic, or acetic acids (Rodríguez and Fraga, 1999). Furthermore, PSB contribute to the cycling of phosphorus in soils by producing enzymes like phosphatases that breakdown organic phosphorus compounds (Richardson and Simpson, 2011).

While these bacteria are found in soils naturally, factors such as pH, moisture content, and organic matter content can have an impact on their populations and levels of activity. By reducing phosphorus immobilization in alkaline calcareous soils, PSB may be able to increase crop yields without significantly relying on chemical fertilizers. Comprehending and utilizing PSB's function in the cycling of phosphorus creates new opportunities for sustainable farming, particularly in areas where phosphorus is scarce.

Objectives and scope of the review

This review aims to give a thorough understanding of the function of phosphorus-solubilizing bacteria in the dynamics of organic matter and phosphorus cycling in alkaline calcareous soils. The methods by which PSB increase phosphorus bioavailability, the relationships between PSB and soil organic matter, and the consequences for sustainable agricultural practices will be the main topics of this review. Additionally, it will discuss how the environment affects PSB activity and offer some possible methods for incorporating PSB into agricultural management techniques. This review attempts to demonstrate the potential of PSB as a crucial element in enhancing phosphorus use efficiency and general soil health by summarizing the available research.

Phosphorus in Alkaline Calcareous Soils

Soil chemistry and phosphorus availability

The pH and calcium carbonate content of the soil have a significant impact on the phosphorus (P) dynamics in alkaline calcareous soils (Paul and Clark, 1996). The pH range of alkaline soils is usually between 7 and 9 points, which significantly lowers the solubility of phosphorus. Phosphorus has a tendency to bind with calcium ions as soil pH rises, forming calcium-phosphate compounds like apatite, tricalcium phosphate, and dicalcium phosphate (Kamprath, 1985). Because these substances are very insoluble in alkaline environments, plants cannot absorb phosphorus. Even in soils with sufficient total phosphorus content, this immobility causes phosphorus deficiency (Brownrigg et al., 2022).

Alkaline calcareous soils' high pH inhibits the biological activity of microorganisms that break down organic matter

https://doi.org/10.55627/agrivet.003.02.844

and mineralize phosphorus. In many soils, organic matter is an important source of phosphorus; however, in alkaline soils, the organic matter's slow breakdown further reduces the amount of phosphorus available. Furthermore, calcium-organic complexes, which sequester phosphorus in forms that are difficult for plants to access, can form as a result of the interaction between calcium and organic matter compounds (Hinsinger, 2001). Calcium in soils binds with organic acids, forming stable complexes, as represented below;

$Ca^{2+} + 2RCOO^{-} \rightarrow Ca(RCOO)_2$ (1)

Phosphorus is therefore a critically limiting nutrient in these soils due to the combination of high pH, high calcium content, and low microbial activity, requiring the use of alternate techniques to increase phosphorus bioavailability.

Forms of phosphorus in alkaline soils

Soils contain phosphorus in a variety of forms, mainly in the form of organic and inorganic pools. In alkaline calcareous soils, inorganic phosphorus is primarily present as calcium phosphates, which are extremely insoluble at high pH values (Bechtaoui et al., 2021). Apatite, the main phosphorus mineral found in soils, and other calcium-phosphate compounds produced by precipitation reactions in the soil are examples of these inorganic forms. These forms add to the soil's long-term phosphorus reserves because they are not easily absorbed by plants, but they have little direct impact on crop growth.

Another important source of phosphorus is organic phosphorus, which is mostly obtained from microbial and plant waste. Numerous substances, including phospholipids, nucleic acids, and inositol phosphates, contain organic phosphorus. However, microbial processes that decompose organic matter and release phosphorus through mineralization are necessary for the bioavailability of organic phosphorus (Condron and Tiessen, 2005). The difficult soil conditions in alkaline soils cause the microbial breakdown of organic matter to be slowed, which lowers the rate of organic phosphorus turnover.

The availability of phosphorus is largely dependent on the balance between these phosphorus pools. The problem in alkaline soils is getting these pools, especially the inorganic calcium phosphates, into forms that plants can utilise. Both chemical and biological factors impede this process, which limits the effectiveness of phosphorus fertilization and necessitates the use of creative soil management techniques, such as the use of phosphorus-solubilizing bacteria to promote phosphorus cycling.

The following table summarizes the key phosphorus fractions in alkaline calcareous soils and their availability to plants.

Table 1. Soil phosphorus fractions and their availability in alkaline calcareous soils

Phosphorus Fraction	Chemical Composition	Availability to Plants	Reference
Soluble Phosphates	$H_2PO_4^-$, HPO_4^{2-}	High	Kamrath, 1985
Calcium-bound Phosphates	Dicalcium Phosphate ($CaHPO_4$), Tricalcium Phosphate ($Ca_3(PO_4)_2$)	Low	Hüttl & Bens, 2004
Organic Phosphorus	Phospholipids, Nucleic Acids, Inositol Phosphates	Variable	Bronick & Lal, 2005
Adsorbed Phosphates	Phosphorus bound to soil mineral surfaces	Medium	Kamrath, 1985
Residual Phosphorus	Complex, highly stable organic or mineral compounds	Very Low	Cross & Schlesinger, 1995

Challenges in Phosphorus Fertilization

Because of the chemistry of the soil, phosphorus fertilization in alkaline calcareous soils is fraught with difficulties. The quick fixation of phosphorus following fertilizer application is one of the primary problems. The availability of phosphorus for plants is decreased when phosphorus fertilizers are added to alkaline soils because they rapidly combine with calcium ions to form insoluble calcium-phosphate compounds. As a result, a significant amount of applied phosphorus becomes fixed and unavailable for plant uptake, resulting in inefficient phosphorus use (Holford, 1997). Because of this, farmers frequently overapply phosphorus fertilizers in an attempt to meet crop demand, which can have a negative impact on the environment and cause financial losses.

The environmental effects of applying too much phosphorus present another difficulty in phosphorus fertilization. Runoff and leaching can cause the gradual loss of phosphorus that is not used by plants or immobilized in the soil, especially in areas with high rainfall or irrigation. This runoff may lead to algal blooms and a decrease in oxygen levels in aquatic environments by eutrophicating water bodies (Schröder et al., 2011). Because of the strong fixation in alkaline calcareous soils, phosphorus runoff is less of an immediate problem; however, if soil phosphorus levels rise to unsustainable levels, it still poses a long-term problem.

Moreover, the fundamental problem of phosphorus immobilization in these soils is not resolved by the application of traditional phosphorus fertilizers. Improving phosphorus use efficiency requires the application of techniques that increase phosphorus bioavailability, such as organic amendments, microbial inoculants, or alternative fertilization techniques. Creating sustainable fertilization techniques that strike a balance between crop nutrient requirements, environmental preservation, and long-term soil health remains a challenge. In alkaline calcareous soils, biological methods—such as phosphorus solubilizing bacteria offer a viable way to counteract the drawbacks of conventional phosphorus fertilization (Richardson and Simpson, 2011).

Phosphorus Solubilizing Bacteria (PSB) and Their Mechanisms

Types of PSB

A broad class of microorganisms known as phosphorus solubilizing bacteria (PSB) are able to transform insoluble phosphorus into forms that are bioavailable to plants. According to Rodríguez and Fraga (1999), the genera Bacillus, Pseudomonas, Rhizobium, and Azotobacter contain the most frequently studied PSB. These microorganisms are extensively dispersed across diverse soil types, encompassing forest, rhizosphere, and agricultural soils. Among these bacteria, Bacillus and Pseudomonas are especially well-known because of their strong ability to survive and adjust to various environmental conditions. Bacillus species are known to produce endospores, which help them endure harsh environments like low soil nutrients and extremely high temperatures. Additionally, a variety of metabolites that they produce help in the solubilization of phosphorus (Vassilev et al., 2006). However, Pseudomonas species, which are frequently found in the rhizosphere, are very good at generating organic acids that break down phosphorus compounds. Their capacity to settle in the rhizosphere confers significant advantages in terms of stimulating plant development.

Phosphorus solubilization is also facilitated by other PSB, including Rhizobium and Azotobacter, especially when they coexist in symbiotic relationships with leguminous plants. These bacteria play a crucial role in the cycling of nutrients in soils because they fix atmospheric nitrogen in addition to solubilizing phosphorus. PSB are essential for increasing phosphorus availability in soils with low phosphorus bioavailability, such as alkaline calcareous soils, because of their diversity and capacity to flourish in a variety of settings (Bechtaoui et al., 2021).

Following table outlines the main PSB genera and their mechanisms of phosphorus solubilization.

Table 2: Phosphorus Solubilizing Bacteria (PSB) and Their Characteristics

Genus	Key Characteristics	Mechanisms of Phosphorus Solubilization	Reference
Bacillus	Endospore formation, survival in extreme conditions	Organic acid production, enzymatic solubilization	Cross & Schlesinger, 1995
Pseudomonas	Rhizosphere colonization, high adaptability	Organic acid production, especially citric and gluconic	Giusquiani et al., 1995
Rhizobium	Symbiotic with legumes, nitrogen fixation	Phosphate mineral solubilization, organic phosphorus mineralization	Giusquiani et al., 1995
Azotobacter	Nitrogen-fixing, free-living bacteria	Organic acid production and phosphorus solubilization	Vance et al., 1987

Mechanisms of phosphorus solubilization

A variety of biochemical pathways are used by phosphorus-solubilizing bacteria to liberate phosphorus from insoluble mineral forms. The most prevalent and thoroughly researched mechanism involves the synthesis of organic acids. These organic acids, which include gluconic acid, citric acid, and oxalic acid, decrease the pH of the soil microenvironment and cause calcium-phosphate complexes to dissolve. PSB solubilize phosphorus by releasing organic acids, which dissolve calcium-phosphate complexes, as shown in the reaction below:

$Ca_3(PO_4)_2 + 4H^+ \rightarrow 2H_2PO4^- + 3Ca^{2+}$ (2)

For instance, it has been demonstrated that citric acid chelates calcium ions, reducing the amount of phosphorus that is bound to calcium and releasing it into the soil solution (Gyaneshwar et al., 2002). Similar to calcium and magnesium, oxalic acid can also form stable complexes that increase the availability of phosphorus for plant uptake.

Apart from generating organic acids, PSB also generate different enzymes that facilitate the solubilization of phosphorus. For example, phosphatases are an enzyme family that breaks down organic phosphorus compounds into inorganic phosphate, which plants can then absorb (Richardson and Simpson, 2011; Tarafdar and Claassen, 1988). These enzymes' activity is essential for the mineralization of organic phosphorus, which is present in soil organic matter. Because organic phosphorus decomposition in alkaline soils is frequently sluggish, PSB's enzymatic activity is essential for rendering organic phosphorus accessible.

The proton extrusion mechanism is another significant one. Certain PSB cause the surrounding soil particles to become more acidic, which can boost the solubility of phosphorus. Protons, or H+ ions, are released into the soil. Since high pH levels prevent phosphorus from being available in alkaline soils, this process works especially well in these conditions. By neutralizing the negatively charged soil particles, the protons aid in the solubilization of phosphate minerals by facilitating the release of bound phosphorus (Hinsinger, 2001).

These methods are not exclusive; many PSB solubilize phosphorus by combining the production of organic acids, enzyme secretion, and proton extrusion. Numerous variables, such as the pH of the soil, the amount of organic matter in the soil, and the existence of additional soil microorganisms, affect how effective these mechanisms are. PSB-mediated solubilization can greatly increase phosphorus availability for plants in alkaline calcareous soils, where phosphorus availability is particularly limited. This will improve crop growth and soil fertility (Vassilev et al., 2006).

Interactions with other soil microorganisms

Actinomycetes, fungi, and other bacteria are just a few of the many soil microorganisms with which phosphorus-solubilizing bacteria interact. Depending on the composition of the microbial community and the surrounding environment, these interactions can be either symbiotic or competitive. The symbiotic relationship between PSB and arbuscular mycorrhizal (AM) fungi is among the best-known. Through their hyphal networks, AM fungi grow symbiotic relationships with plant roots, increasing the surface area of the roots and improving phosphorus uptake. According to Artursson et al. (2006) PSB can improve the solubilization of phosphorus in the soil, increasing its accessibility to AM fungi, which then transfer the phosphorus to the roots of plants. Plants benefit more from this mutually beneficial relationship when they acquire phosphorus, especially in soils with low phosphorus levels.

On the other hand, competition between PSB and other soil microbes also happens frequently. For instance, in the rhizosphere, PSB and plant growth-promoting rhizobacteria (PGPR) compete with one another for available nutrients and root colonization sites (Khan et al., 2009). The result of this competition may have an impact on other microbial activities related to nutrient cycling as well as the general efficacy of phosphorus solubilization. The activity of PSB may occasionally be suppressed by the presence of antagonistic microorganisms, which lowers their capacity to efficiently solubilize phosphorus.

The general presence of a diverse microbial community is advantageous for soil health and nutrient availability, despite these competitive interactions. PSB frequently have synergistic effects with other beneficial microorganisms to increase soil fertility. For example, certain bacteria have the ability to break down organic materials, releasing phosphorus that PSB can then solubilize. As a result, PSB can aid in the release of additional nutrients that are trapped in the soil matrix, giving plants access to a more balanced nutrient profile (Hüttl and Bens, 2004).

Comprehending the interplay among PSB and other soil microorganisms is imperative for optimizing their application in agricultural contexts, especially in soils with restricted phosphorus availability. Controlling these microbial interactions can result in more sustainable farming methods and increased nutrient utilization efficiency.

Role of PSB in Phosphorus Cycling in Alkaline Soils

Enhancement of phosphorus bioavailability

Since phosphorus is frequently bound to calcium in forms that are difficult for plants to access, phosphorus solubilizing bacteria (PSB) are essential to increasing the bioavailability of phosphorus (P) in alkaline soils (Sharma et al., 2013).

The solubilization of these inorganic phosphate compounds is the main mechanism by which PSB increase phosphorus availability. As was previously mentioned, PSB produce organic acids that lower the pH of the microenvironment around the root zone, such as citric acid, oxalic acid, and gluconic acid. The dissolution of calcium-phosphate complexes brought about by this acidification process releases phosphorus into the soil solution in a form that is easily absorbed by plants (Gyaneshwar et al., 2002).

Additionally, PSB secrete enzymes that convert organic phosphorus compounds into inorganic phosphate, such as phosphatases. These enzymes are especially helpful in soils that have a high percentage of phosphorus bound up in organic matter, like phospholipids or nucleic acids. According to Richardson and Simpson (2011), PSB's enzymatic mineralization of organic phosphorus contributes to a steady supply of phosphorus that is available for plant uptake all through the growing season. PSB are important players in improving phosphorus cycling because of their dual action of solubilizing inorganic phosphorus and mineralizing organic phosphorus. This is especially true in alkaline calcareous soils where phosphorus fixation is a significant problem.

In addition to increasing plants' availability of phosphorus, PSB lessen the need for chemical fertilizers, which are frequently overapplied in alkaline soils to make up for phosphorus deficiencies. Enhancing the efficiency of phosphorus use allows PSB to support more environmentally friendly agricultural practices by mitigating the negative effects of excessive phosphorus application on the environment, such as runoff and eutrophication in neighboring water bodies (Bechtaoui et al., 2021).

Role of PSB in organic matter dynamics

Phosphorous solubilizing bacteria's capacity to break down organic phosphorus compounds is intimately related to their function in the dynamics of organic matter. Organic matter serves as a storehouse for nutrients, including phosphorus, in soils. However, because of their high pH and low microbial activity, alkaline calcareous soils frequently have a sluggish rate of organic matter decomposition. By generating extracellular enzymes that mineralize organic phosphorus and facilitate its release from organic materials, PSB aid in the breakdown of organic matter(Condron and Tiessen, 2005).

Additionally, PSB interacts with bacteria and other saprophytic fungi that are also involved in the breakdown of organic matter in the soil. By encouraging the breakdown of plant and microbial residues, which releases not only phosphorus but also other vital nutrients like nitrogen and carbon, these interactions improve nutrient cycling. Plants can access the mineralized phosphorus, and the PSB and other microorganisms use the organic carbon as a source of energy to continue their activities (Bronick and Lal, 2005). The decomposition of organic matter is accelerated by the synergistic interaction between PSB and the larger soil microbial community, enhancing soil structure, water retention, and fertility in general.

Additionally, PSB contribute to carbon sequestration by accelerating the breakdown of organic matter. A portion of the carbon that is stabilized in soil aggregates during the breakdown of organic matter aids in soil sequestration and helps lessen the effects of climate change (Lal, 2004). PSB aid in the upkeep of healthy, productive soils by promoting the cycling of phosphorus and the dynamics of organic matter, particularly in situations where nutrient availability is constrained, like alkaline calcareous soils.

Influence of Environmental Factors

The pH, temperature, and moisture content of the soil are among the environmental factors that affect PSB activity and efficiency. These elements have the ability to either facilitate or impede the solubilization processes, which affects how much phosphorus is available to plants.

pH: One of the most important variables influencing PSB activity is the pH of the soil. Although PSB are especially helpful in alkaline soils, their capacity to generate organic acids and solubilize phosphorus may be hindered by extremely high pH levels. The majority of PSB grow best in environments that range from mildly acidic to neutral because their acid production dissolves calcium-phosphate complexes more effectively there. However, the buffering ability of calcium carbonate, which neutralizes the acids produced by the bacteria, can lessen the effectiveness of PSB in extremely alkaline conditions (pH > 8) (Hinsinger, 2001).

Temperature: Enzyme activity and microbial growth are impacted by temperature. Similar to other soil microorganisms, PSB have a preferred temperature range of 20 to 30 degrees Celsius for optimal activity. Microbial metabolism slows down in colder environments, which lowers the amount of organic acids and enzymes produced that are required for the solubilization of phosphorus. On the other hand, exceptionally high temperatures have the potential to cause enzyme denaturation and the demise of delicate microbial populations. Thus, variations in temperature can have a major effect on PSB's ability to bind phosphorus in the soil (Khan et al., 2009).

Moisture: Another important component is soil moisture since water is required for microbial metabolism, organic acid diffusion, and solubilized phosphorus diffusion throughout the soil matrix. PSB activity can be severely limited in arid and semi-arid regions, where moisture levels are frequently low. On the other hand, anaerobic conditions may arise in overly wet soils, which will prevent aerobic PSB from growing and promote other microbial processes

that are not involved in phosphorus solubilization (Hüttl and Bens, 2004). Therefore, to preserve PSB activity and improve phosphorus availability in agricultural systems, proper management of soil moisture is crucial.
The table below highlights the environmental factors that affect PSB activity and phosphorus solubilization.

Table 3. Environmental factors affecting PSB activity.

Environmental Factor	Effect on PSB Activity	Reference
Soil pH	High pH inhibits organic acid production, affecting phosphorus solubilization	Drinkwater et al. (1998)
Temperature	Optimal range 20–30°C; lower temperatures slow microbial activity	Six et al. (1999)
Moisture Content	Affects microbial metabolism; low moisture limits PSB activity, while excessive moisture may create anaerobic conditions	Kern and Johnson (1993)

Case studies in alkaline calcareous soils

The efficiency of PSB in raising phosphorus availability in alkaline calcareous soils has been demonstrated in a number of case studies. For instance, studies carried out by Vassilev et al. (2006) showed that crop yields and phosphorus availability in alkaline soils were considerably enhanced by applying PSB in conjunction with organic amendments. In this investigation, soils supplemented with decomposed organic matter were inoculated with strains of *Bacillus* and *Pseudomonas*. The findings demonstrated that the bacteria significantly enhanced plant growth by both solubilizing phosphorus from inorganic sources and accelerating the breakdown of organic phosphorus.
An additional Deng et al. (2023) study investigated the application of PSB-enriched organic fertilizers in saline-alkaline soils. The researchers discovered that the inclusion of PSB improved the structure of the microbial community and raised the amount of phosphorus and other nutrients that were available. This study also showed that PSB can enhance the physical characteristics of soil, such as water retention and aggregate stability, which enhances soil fertility and plant health.
Phosphorous solubilizing bacteria have been effectively used to reduce phosphorus deficiency in alkaline soils in arid parts of the Middle East. One study that Ryan (2009) in Syria discovered that introducing phosphorus-solubilizing bacteria specifically, *Pseudomonas* into the soil significantly increased the amount of phosphorus that wheat crops absorbed. Additionally, the researchers found that using PSB made using chemical phosphorus fertilizers less necessary, improving the practice's sustainability and financial viability for farmers.
These case studies show how PSB can boost phosphorus availability and boost soil health in calcareous alkaline soils. Farmers can boost crop yields, improve nutrient management, and lessen the environmental impact of phosphorus fertilization by incorporating PSB into their farming practices.

Organic Matter and PSB Interactions

Organic matter as a nutrient source for PSB

In soils that are low in nutrients, such as alkaline calcareous soils, organic matter is essential for the development and activity of phosphorus solubilizing bacteria (PSB). Decomposing plant and microbial residues make up organic matter, which provides soil microorganisms with vital nutrients like carbon and nitrogen (Tisdall and OADES, 1982). Because organic matter offers a consistent supply of carbon, which is essential for PSB metabolism and energy production, it is especially significant to them (Bronick and Lal, 2005).
PSB flourish in high-organic matter soils because readily decomposable carbon compounds are present. These substances stimulate bacterial growth and allow them to generate the organic acids and enzymes needed to solubilize phosphorus. For instance, sugars, amino acids, and organic acids are released during the breakdown of organic materials like manure and plant leftovers, and these substances encourage the growth of microorganisms like PSB. Thus, PSB use these carbon sources to produce organic acids like lactic, citric, and oxalic acids that solubilize insoluble phosphate minerals and lower the pH of the soil(Rodríguez and Fraga, 1999).
Furthermore, PSB can obtain phosphorus from organic matter that would not otherwise be available to plants because organic matter can act as a reservoir for organic phosphorus. By creating enzymes like phosphatases, which hydrolyze organic phosphorus into plant-available inorganic phosphate, PSB make use of organic phosphorus compounds (Richardson and Simpson, 2011). Thus, the relationship between PSB and organic matter improves soil fertility overall by increasing phosphorus cycling and bacterial activity. Because phosphorus is frequently scarce in

alkaline calcareous soils, the presence of organic matter is essential for preserving a healthy PSB population and fostering the solubilization processes of PSB.
The table below shows how organic matter influences PSB activity and soil fertility.

Table 4. Organic matter's role in PSB activity

Aspect of Organic Matter	Role in PSB Activity	Impact on Soil Fertility	Reference
Carbon Source	Provides energy for PSB, promoting organic acid production	Enhances PSB growth and phosphorus solubilization	Turner et al. (2003)
Phosphorus Release	Organic matter contains organic phosphorus	Organic phosphorus is mineralized into bioavailable forms	Whitelaw (1999)
Soil Structure Improvement	Organic matter contributes to soil aggregation	Improves water retention and reduces erosion	Whitelaw (1999)

Impact of PSB on organic matter decomposition

Additionally, PSB actively participate in the breakdown of complex organic compounds and the release of nutrients necessary for plant growth in the decomposition of organic matter in soils. Through their interactions with other soil microorganisms involved in organic matter decomposition, PSB indirectly influence organic matter dynamics, even though their primary function is phosphorus solubilization. PSB decompose organic matter, contributing to nutrient cycling through reactions like this;

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \qquad (3)$$

The activity of decomposers, such as saprophytic fungi and bacteria, which depend on a balanced nutrient supply for effective organic matter breakdown, is facilitated by PSB by increasing phosphorus availability (Condron and Tiessen, 2005).

By increasing nutrient availability, PSB can quicken the decomposition of organic matter in alkaline soils, where high pH and calcium content frequently cause organic matter breakdown to proceed slowly. In addition to solubilizing phosphorus, PSB's organic acids also aid in the general breakdown of organic matter. These acids aid in the dissolution of organic compounds linked to minerals, increasing their accessibility for microorganisms involved in decomposition. Further nutrients, such as nitrogen, sulfur, and trace elements, are released as a result of the breakdown of organic matter, supporting the growth of microorganisms and plants (Giusquiani et al., 1995).

In agricultural soils, where maintaining a high level of organic matter is essential for soil structure, water retention, and nutrient cycling, PSB's role in organic matter decomposition is especially significant. PSB contribute to the creation of humus, a stable form of organic matter that improves soil fertility and resilience, by encouraging the breakdown of organic residues (Lichter, 2008). This procedure is crucial in alkaline calcareous soils because poor organic matter turnover and phosphorus fixation frequently interfere with nutrient cycling in these soil types. By enhancing phosphorus solubilization and organic matter decomposition, PSB activity helps to mitigate these issues and creates healthier, more productive soils.

Contribution of PSB to carbon sequestration

The PSB have an impact on the decomposition and stabilization of organic matter, which helps with carbon sequestration in soils in addition to their function in the cycling of nutrients. By lowering the amount of carbon dioxide in the atmosphere, carbon sequestration—the long-term storage of carbon in soils—is crucial for reducing the effects of climate change. PSB facilitate the incorporation of organic carbon into stable soil aggregates, where it can be stored for long periods of time, by encouraging the breakdown of organic matter (Lal, 2004).

Humus, a stable organic compound rich in carbon, is closely associated with the process of sequestering carbon in soils. A portion of the carbon in organic matter is mineralized during its breakdown and is released as carbon dioxide by microorganisms. The remaining carbon is integrated into the soil matrix. By speeding up the breakdown of organic residues, PSB contribute to this process by forming humic substances that are more resistant to further decomposition. According to Kögel-Knabner (2002), these humic materials combine with soil minerals to form stable aggregates that shield organic carbon from microbial deterioration and prolong its sequestration in the soil (Kögel-Knabner, 2002).

Furthermore, carbon sequestration is indirectly supported by PSB's capacity to increase phosphorus availability. A crucial nutrient for plant growth is phosphorus, and increased phosphorus availability encourages the production of more biomass by plants. Plants absorb carbon dioxide from the atmosphere during growth and photosynthetic processes, converting it into organic matter that eventually finds its way back into the soil as plant residues. PSB promote the synthesis of more organic carbon in the form of plant biomass by raising the availability of phosphorus, which can eventually be stored in soils (Kögel-Knabner, 2002).

In alkaline calcareous soils, where decomposition of organic matter is frequently restricted, PSB activity is essential for carbon storage and nutrient cycling. In addition to improving soil health and fertility, PSB help with the long-term sequestration of carbon in these soils by encouraging the turnover of organic matter and the formation of stable soil aggregates. This helps to slow down the effects of climate change.

Agricultural and Environmental Implications

Role of PSB in sustainable agriculture

The utilization of phosphorus solubilizing bacteria (PSB) as biofertilizers presents a promising avenue for application and provides a sustainable substitute for traditional chemical fertilizers. The goal of sustainable agriculture is to maintain crop productivity and soil fertility while reducing the amount of environmental degradation. By increasing the bioavailability of phosphorus, a crucial nutrient, PSB help achieve this goal without requiring excessive inputs of chemical fertilizers (Richardson and Simpson, 2011). In order to meet crop demands, chemical phosphorus fertilizers are frequently applied in large quantities, especially in soils with low phosphorus bioavailability like alkaline calcareous soils. Unfortunately, the chemistry of the soil immobilizes a large portion of the applied phosphorus, resulting in inefficient phosphorus use.

The requirement for phosphorus fertilizers is decreased by PSB by solubilizing phosphate compounds that are naturally present in the soil. In order to liberate phosphorus from its bound forms and make it available to plants, PSB produce organic acids and enzymes. Consequently, there is less need for synthetic fertilizers, which lowers the financial burden on farmers as well as the negative environmental effects of excessive fertilizer use (Vassilev et al., 2006). By encouraging microbial diversity and soil health, this strategy not only improves phosphorus efficiency but also adds to the overall sustainability of farming practices.

Organic farming, reduced tillage, and integrated nutrient management are among the sustainable agricultural practices that are supported by the use of PSB as biofertilizers. By reducing chemical inputs and promoting a more balanced nutrient cycling process, PSB integration improves soil fertility over the long term in agricultural systems (Yadav et al., 2000). Additionally, PSB can be used to improve soil productivity in areas where conventional fertilizers are less effective due to their ability to thrive in a variety of environments, including nutrient-poor and alkaline soils. In addition to increasing crop yields, farmers can reduce their environmental impact by encouraging the use of PSB in agriculture.

The following table summarizes PSB’s contributions to sustainable agriculture and environmental benefits.

Table 5: PSB's contribution to sustainable agriculture.

Contribution	Description	Impact on Sustainability	Reference
Improved Phosphorus Use Efficiency	PSB increases phosphorus bioavailability, reducing the need for fertilizers	Reduces environmental harm, saves costs	Follett (1981)
Soil Fertility Enhancement	PSB improves organic matter decomposition and nutrient cycling	Increases long-term soil health	Smith and Read (2010)
Reduction in Chemical Fertilizer Usage	PSB solubilizes natural phosphorus reserves, reducing fertilizer inputs	Lowers risk of runoff and eutrophication	Zhou (2019)

Environmental Impacts of PSB-Mediated Phosphorus Cycling

The PSB-mediated phosphorus cycling has a number of advantages for the environment, most notably that it lessens the harmful effects of chemical phosphorus fertilizers. Phosphorus runoff, which happens when too much phosphorus from fertilizers is washed from fields into neighboring water bodies, is one of the main environmental issues with phosphorus fertilization. Runoff like this has the potential to cause eutrophication, a condition in which an excess of algal growth results from nutrient enrichment, lowering oxygen levels in aquatic environments, killing fish, and reducing biodiversity (Schröder et al., 2011).

The risk of phosphorus runoff can be decreased by PSB by increasing the solubility and uptake efficiency of phosphorus in soils, which in turn helps decrease the need for excessive fertilizer application. By facilitating the release of phosphorus already present in the soil, PSB reduce the amount of phosphorus that is added from outside sources. By increasing phosphorus use efficiency, this method not only lowers the chance of nutrient leaching but also makes sure that more of the available phosphorus is used by plants rather than lost to the environment(Zhang et al., 2022).

Moreover, utilizing PSB in agriculture can help lessen soil erosion and enhance soil structure. PSB improve soil aggregation, which increases water retention and decreases surface runoff, through their interactions with organic matter and other soil microorganisms. This helps avoid soil erosion and nutrient loss, especially in areas that frequently receive irrigation or high rainfall (Hüttl and Bens, 2004). Long-term improvements in soil structure also boost soil resilience and fertility, promoting sustainable land management techniques (Zhang et al., 2023).

Even with these advantages for the environment, using PSBs may come with some risks. The potential for unexpected ecological effects when introducing microbial inoculants into natural ecosystems is one thing to be concerned about. Although PSB are generally advantageous, changes in the composition of the microbial community may result from their interactions with native soil microorganisms. This might upset natural beneficial microorganism balances or outcompete them, which could have a detrimental impact on soil biodiversity (Khan et al., 2009). Therefore, to reduce ecological risks, careful consideration of the particular PSB strains used and their compatibility with local ecosystems is crucial.

In conclusion, by lowering the need for chemical fertilizers, reducing phosphorus runoff, and improving soil health, PSB-mediated phosphorus cycling offers encouraging environmental benefits. To guarantee that the benefits to the environment do not diminish, microbial inoculants' possible hazards must be controlled by appropriate application techniques. It is feasible to strike a balance between environmentally friendly farming practices and productive agriculture by incorporating PSB into sustainable farming systems.

Challenges and Future Research Directions

Limitations in current understanding of PSB

Even though our knowledge of phosphorus solubilizing bacteria (PSB) has advanced significantly, there are still a number of important research gaps, especially when it comes to their mechanisms, practical uses, and scalability. Although a great deal of information is known about how PSB produce organic acids and engage in enzymatic activity to solubilize phosphorus, little is known about the precise pathways and genetic controls that regulate these processes. For instance, more research is needed to fully understand the range of genes involved in phosphorus solubilization and how they react to various environmental cues like the pH of the soil or the amount of organic matter present. This information is essential for maximizing PSB strain performance in a variety of soil environments, especially difficult ones like alkaline calcareous soils(Richardson and Simpson, 2011).

The challenge of transferring laboratory results to field applications is another drawback. PSB frequently exhibit high phosphorus solubilization potential in controlled settings, but a variety of biotic and abiotic factors can cause inconsistent performance in the field. PSB activity can be greatly influenced by soil characteristics such as pH, moisture, and organic matter content, as well as by interactions with native soil microorganisms. Furthermore, because microbial inoculants' efficacy can deteriorate over time as a result of environmental stresses or competition from native microbes, the scalability of PSB applications in large-scale agricultural systems presents difficulties. To evaluate PSB's resilience and applicability as biofertilizers in various agroecological zones, long-term field studies are required (Vassilev et al., 2006).

Furthermore, little is known about the interactions between PSB and other nutrient cycles, like the nitrogen or potassium cycles. Research on multipurpose microbes that can both cycle other nutrients and solubilize phosphorus would be helpful in creating integrated nutrient management plans that simultaneously address a variety of soil fertility problems.

Technological advancements and potential for PSB use

Technological developments in biotechnology and molecular biology present encouraging paths toward increasing PSB's effectiveness in agriculture (Zhang et al., 2002). The identification and modification of important genes involved in phosphorus solubilization is one area of focus. Researchers can identify the genes responsible for the synthesis of organic acids, the secretion of enzymes, and other phosphorus-solubilizing processes by using transcriptome and genomic analyses. These characteristics might be improved by using genetic engineering techniques, leading to PSB strains that are better able to solubilize phosphorus even in the presence of unfavorable soil conditions, like high pH or low organic matter content (Gyaneshwar et al., 2002).

The field of biotechnology presents the possibility of creating multipurpose microbial consortiums by merging PSB with additional advantageous microorganisms, like mycorrhizal fungi or nitrogen-fixing bacteria. By addressing several nutrient deficiencies at once, these consortiums can increase overall nutrient availability and promote plant growth. Such cooperative relationships between various microorganisms may result in biofertilizers that are more effective and resilient, able to function well in a range of soil conditions. Additionally, by predicting the ideal microbial species combinations for particular soil conditions, bioinformatics tools and machine learning can be used to optimize biofertilizer formulations for various crops and environments (Bechtaoui et al., 2021).

Utilizing nanotechnology to enhance PSB efficacy and delivery is a promising new technological development. PSB can be encased in nanomaterials to improve their survival and activity in the soil while shielding them from environmental stresses. This strategy might increase PSB's durability in the field and guarantee more steady phosphorus solubilization over time. According to Naderi and Danesh-Shahraki (2013), nanotechnology may also make it possible to deliver PSB specifically to the root zone, where their activity is most advantageous for plant growth.

CONCLUSION

The present review has emphasized the crucial function of phosphorus solubilizing bacteria (PSB) in augmenting the bioavailability of phosphorus. This is especially true in alkaline calcareous soils, where phosphorus is frequently immobilized in forms that are inaccessible to plants. PSB successfully liberate phosphorus from both inorganic and organic sources by combining the production of organic acid, enzymatic activity, and proton extrusion. The interplay between PSB and organic matter facilitates the breakdown of organic residues and increases carbon sequestration, which improves soil fertility and contributes to the cycle of nutrients. In addition to encouraging a sustainable cycle of phosphorus, PSB also lessen the need for chemical fertilizers, lowering the risk of phosphorus runoff and eutrophication to the environment. But there are still questions about their mechanisms, scalability, and field effectiveness, which makes more research into how best to use them in different soil types and conditions necessary. Going forward, there is a great deal of promise for enhancing soil health and nutrient management through the incorporation of PSB into sustainable agricultural systems. The efficiency and dependability of PSB will probably be improved by developments in molecular biology, biotechnology, and nanotechnology, opening up new avenues for their extensive use as biofertilizers. PSB present a viable option for enhancing crop productivity, lowering the environmental impact of agricultural practices, and fostering sustainable phosphorus cycling as farmers look for more ecologically friendly substitutes for chemical fertilizers.

AUTHOR CONTRIBUTIONS

All authors contributed equally to this research.

COMPETING OF INTEREST

The authors declare no competing interests.

REFERENCES

Artursson, V., Finlay, R.D., Jansson, J.K., 2006. Interactions between arbuscular mycorrhizal fungi and bacteria and their potential for stimulating plant growth. Environmental Microbiology 8, 1-10.

Bechtaoui, N., Rabiu, M.K., Raklami, A., Oufdou, K., Hafidi, M., Jemo, M., 2021. Phosphate-dependent regulation of growth and stresses management in plants. Frontiers in Plant Science 12, 679916.

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3-22.

Brownrigg, S., McLaughlin, M.J., McBeath, T., Vadakattu, G., 2022. Effect of acidifying amendments on P availability in calcareous soils. Nutrient Cycling in Agroecosystems 124, 247-262.

Condron, L.M., Tiessen, H., 2005. Interactions of organic phosphorus in terrestrial ecosystems, Organic phosphorus in the environment. CABI publishing Wallingford UK, pp. 295-307.

Deng, P.-B., Guo, L.-P., Yang, H.-T., Leng, X.-Y., Wang, Y.-M., Bi, J., Shi, C.-F., 2023. Effect of an organic fertilizer of ganoderma lucidum residue on the physical and chemical properties and microbial communities of saline alkaline soil. Water 15, 962.

Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262-265.

Follett, R., 1981. Utilization and management of animal manure. In Manure Management (pp. 1-12). American Society of Agricultural Engineers.

Giusquiani, P.L., Pagliai, M., Gigliotti, G., Businelli, D., Benetti, A., 1995. Urban waste compost: Effects on physical, chemical, and biochemical soil properties. Journal of Environmental Quality 24, 175-182.

Gyaneshwar, P., Naresh Kumar, G., Parekh, L., Poole, P., 2002. Role of soil microorganisms in improving P nutrition of plants. Plant and Soil 245, 83-93.
Hinsinger, P., 2001. Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. Plant and Soil 237, 173-195.
Holford, I., 1997. Soil phosphorus: its measurement, and its uptake by plants. Soil Research 35, 227-240.
Hüttl, R.F., Bens, O., 2004. Plant litter-decomposition, humus formation and carbon sequestration. Journal of Plant Physiology 161, 1185-1186.
Kamprath, E.J., 1985. Soil Nutrient Bioavailability—A Mechanistic Approach. Soil Science 140, 158.
Kern, J., Johnson, M., 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Science Society of America Journal 57, 200-210.
Khan, M.S., Zaidi, A., Wani, P.A., Oves, M., 2009. Role of plant growth promoting rhizobacteria in the remediation of metal contaminated soils. Environmental Chemistry Letters 7, 1-19.
Kögel-Knabner, I., 2002. The macromolecular organic composition of plant and microbial residues as inputs to soil organic matter. Soil Biology and Biochemistry 34, 139-162.
Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623-1627.
Lichter, K., 2008. Effects of tillage and residue management on soil organic matter in a rainfed wheat-fallow system in the Middle East. Soil and Tillage Research 100, 195-203.
Naderi, M., Danesh-Shahraki, A., 2013. Nanofertilizers and their roles in sustainable agriculture. International Journal of Agriculture and Crop Sciences 5, 2229-2232.
Paul, E., Clark, F., 1996. Soil microbiology and biochemistry Academic Press. New York, USA 378.
Raghothama, K., 1999. Phosphate acquisition. Annual review of Plant Biology 50, 665-693.
Richardson, A.E., Simpson, R.J., 2011. Soil microorganisms mediating phosphorus availability update on microbial phosphorus. Plant Physiology 156, 989-996.
Rodríguez, H., Fraga, R., 1999. Phosphate solubilizing bacteria and their role in plant growth promotion. Biotechnology Advances 17, 319-339.
Ryan, J., Masri, Z., & Ibrikci, H., 2009. Significance of gypsum in arid regions: The case of Syria. International Journal of Agriculture & Biology 11, 469-474.
Schröder, J., Smit, A., Cordell, D., Rosemarin, A., 2011. Improved phosphorus use efficiency in agriculture: a key requirement for its sustainable use. Chemosphere 84, 822-831.
Sharma, S.B., Sayyed, R.Z., Trivedi, M.H., Gobi, T.A., 2013. Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. SpringerPlus 2, 1-14.
Six, J., Elliott, E., Paustian, K., 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Science Society of America Journal 63, 1350-1358.
Smith, S.E., Read, D.J., 2010. Mycorrhizal symbiosis. Academic press.
Tarafdar, J., Claassen, N., 1988. Organic phosphorus compounds as a phosphorus source for higher plants through the activity of phosphatases produced by plant roots and microorganisms. Biology and Fertility of Soils 5, 308-312.
Tisdall, J.M., OADES, J.M., 1982. Organic matter and water-stable aggregates in soils. Journal of Soil Science 33, 141-163.
Turner, B.L., Cade-Menun, B.J., Westermann, D.T., 2003. Organic phosphorus composition and potential bioavailability in semi-arid arable soils of the western United States. Soil Science Society of America Journal 67, 1168-1179.
Vassilev, N., Medina, A., Azcon, R., Vassileva, M., 2006. Microbial solubilization of rock phosphate on media containing agro-industrial wastes and effect of the resulting products on plant growth and P uptake. Plant and Soil 287, 77-84.
Whitelaw, M.A., 1999. Growth promotion of plants inoculated with phosphate-solubilizing fungi. Advances in Agronomy 69, 99-151.
Yadav, R.L., Singh, R.S., Lal, R., 2000. Sustainable development of dryland agriculture in India. Advances in Agronomy 71, 133-189.
Zhang, J., Dolfing, J., Liu, W., Chen, R., Zhang, J., Lin, X., Feng, Y., 2022. Beyond the snapshot: identification of the timeless, enduring indicator microbiome informing soil fertility and crop production in alkaline soils. Environmental Microbiome 17, 25.
Zhang, N., Wang, M., Wang, N., 2002. Precision agriculture-A worldwide overview. Computers and Electronics in Agriculture 36, 113-132.
Zhang, P., Jiang, Z., Wu, X., Lu, Q., Lin, Y., Zhang, Y., Zhang, X., Liu, Y., Wang, S., Zang, S., 2023. Effects of biochar and organic additives on CO2 emissions and the microbial community at two water saturations in saline–alkaline soil. Agronomy 13, 1745.
Zhou, J., 2019. Organic matter stabilization by mineral protection in calcareous soils of arid ecosystems. Geoderma 337, 573-584.