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Review Article

Systematic Analysis of Bacterial Efficacy For Phosphate Solubilization in Water Ecosystems: A Systematic Review

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ABSTRACT

The primary aim of managing phosphorus in water is to minimize the risk of eutrophication by utilizing phosphate-solubilizing bacteria as a crucial member of bacterial communities in water ecosystems. These bacteria can solubilize insoluble phosphate compounds, providing a source of phosphorus for aquatic organisms. This study aimed to evaluate the effectiveness of bacteria in solubilizing insoluble phosphorus compounds based on phosphate solubilization index (PSI), phosphate solubilization (mg/L), and pH reduction, using research articles published between 2012 and 2022. A total of 3,005 research articles were gathered from Scopus, ScienceDirect, ProQuest, and Google Scholar. The screening process followed the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) guidelines, which resulted in selecting ten (10) articles that fulfilled the study criteria. The PSI of the bacteria examined in the studies ranged between 0.9 cm and 4.7 cm. The highest PSI was observed in *Bacillus idriensis*, which was isolated from sediment in a lake, while the lowest PSI was found in *Streptomyces violascens, Streptomyces cinereorectus,* and *Angustibacter luteus,* which were isolated from marine environments on an island. The PSP (mg/L) levels varied from 1.3 mg/L to 430.40 mg/L. *Enterobacter asburiae,* isolated from the rhizosphere of a wetland, displayed the highest concentration, while *Burkholderia cenocepacia,* isolated from a wetland paddy field, showed the lowest concentration. Therefore, effective phosphorus management using PSB is essential to minimize phosphate loss, facilitate phosphorus uptake by aquatic organisms, and safeguard water ecosystems from phosphorous pollution sources.

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Introduction

Phosphorus plays a crucial role in the growth and development of living organisms [1]. While it is essential for nourishment, its impact on the natural balance of water ecosystems is not significant [2]. However, introducing excess phosphorus pollutants into water systems increases surface water eutrophication, negatively affecting ecological productivity and water quality for various purposes, including industrial, agricultural, and domestic use [3,4]. According to [5], nearly 90% of the phosphorus transported by rivers is particulate phosphorus, which causes the accumulation of organic and inorganic phosphorus on the riverbed, degrading the water quality [6]. Research indicates that phosphorus release from sediments substantially impacts its concentration in water bodies and the dynamics at the sediment-water interface [7,8]. Sediment particles in aquatic ecosystems possess a high capacity for absorbing nutrients and pollutants, which play a critical role in determining the release of phosphorus from sediments [9].

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A study of over 2,000 water bodies found that 63.1% exhibited excess nutrient contamination, with exceptionally high concentrations observed in eastern Asia, northern Africa, and central and southeastern North America [10]. However, many studies have emphasized the significance of phosphorus as a critical issue, especially in freshwater bodies, and its occurrence, severity, and scale continue to increase worldwide [11,12].

Phosphate-solubilizing bacteria (PSB) inhabit various environments, such as coastal sediments and urban stormwater, represented by species such as *Pseudomonas, Enterobacter, Bacillus, Rhizobium, Aeromonas, Acinetobacter, Flavobacterium,* and *Burkholderia* [13,14,15]. They are essential for converting insoluble phosphate compounds to soluble compounds, which is vital for nutrient cycling and availability, as it allows aquatic organisms to access phosphorus, a crucial element required for their growth and development [16].

Solubilization of phosphorous by PSB primarily begins with forming mineral compounds that act as solvents, such as organic acids, siderophores, protons, hydroxyl ions, and CO^3 [17]. Organic acids, including their carboxyl and hydroxyl cations, effectively bind to cations and lower pH, promoting phosphorus release, thus enhancing phosphate ion availability for biological uptake [18].

However, using PSB in water ecosystems to facilitate phosphate solubilization (PS) can lead to over-fertilization [19], promoting harmful algal blooms and impairing water quality. Furthermore, their introduction

can lead to the displacement of native species, alter biodiversity, and affect ecosystem balance [18]. Therefore, caution, thorough monitoring, and risk assessment are essential to minimize negative impacts and ensure sustainable management practices. While these bacteria may indicate PS, relying solely on them as indicators may overlook broader ecological impacts. Although extensive research has been conducted on the capacity of bacteria to release phosphorus from soil and agro-industrial settings, more attention must be paid to water ecosystems.

Consequently, studies by PSB in water ecosystems are scarce, and the implications of these findings may not be universally applicable to other ecosystems. Hence, the objective of this study was to evaluate the efficacy of PSB in dissolving insoluble phosphorus compounds and identify the different species examined for their capacity to dissolve phosphorus in different water environments.

2.Materials and methods

2.1 Article searching

This study systematically searched articles on the effectiveness of bacteria in solubilizing insoluble phosphate compounds in water ecosystems worldwide. Relevant published data were gathered through the Scopus, Science Direct, ProQuest, and Google Scholar databases. Search terms were explicitly used in combination with Boolean Operators ("AND" or "OR"), as shown in Table 1. This approach helped identify and organize the literature on bacterial PS in diverse water ecosystems.

***Table* 1:** Search terms with Boolean operators

S/n	Subject	Search terms
1	Bacteria	"Phosphate-solubilizing bacteria" "Organic phosphate-solubilizing bacteria" "Inorganic phosphate-solubilizing bacteria"
2	Phosphorous	"Organic phosphate OR inorganic phosphate"
3	Phosphorous management	"Phosphate solubilization" "Phosphate bioremediation" "Phosphate mineralization" "Phosphate hydrolyzation".
4	Water ecosystems	"River water AND sediment" "Marine coastal water" "Island sediment" "Lake water AND sediment" "Lake wetland."

2.2 Article screening

The study strictly adhered to specific inclusion and exclusion criteria aligned with its objectives. Consequently, only complete research articles published in English between January 2012 and December 2022 were considered, focusing on bacterial efficiency to solubilize phosphate in global water ecosystems.

Articles that did not meet these criteria were excluded. The articles retrieved from the databases underwent screening and selection processes using RAYYAN software and were guided by the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) checklist. The screening involved evaluating the titles, abstracts, and full texts of the articles, as established by [20].

2.3 Data extraction

After the thorough screening, articles that met the inclusion criteria were selected for the analysis. Data from these articles, which focused on the phosphate solubilization index (PSI), phosphate solubilization production (PSP), optimum solubilization pH, and the types of PSB in various water ecosystems, were extracted.

3. Results and discussion

The search targeted bacteria capable of solubilizing phosphate in water ecosystems worldwide, resulting in 3,005 articles retrieved from the four online databases (Figure 1). After removing 304 duplicates, 2,674 articles were excluded during title and abstract screening. A thorough examination of the remaining 27 studies at the manuscript level led to the selection of 10 studies that met the inclusion criteria according to PRISMA guidelines.

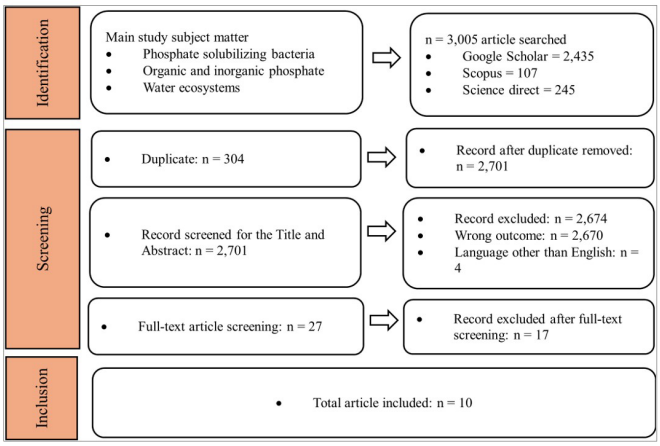


Figure 1: Articles searched and screened using the PRISMA guidelines.

The number of articles retrieved reflects the scientific community's interest in phosphorus pollution and its environmental and ecological implications.

Phosphates in natural water bodies can contribute to water pollution by promoting the growth of aquatic plants and plankton, which negatively affect the health of communities around rivers [21,22].

It stated that excessive levels of phosphorus pollutants in water, resulting from various community activities, can cause the rapid growth of algal blooms. These blooms, in turn, reduce oxygen levels, pose a threat to aquatic organisms, and disrupt the water ecosystems.

Nutrient enrichment, particularly phosphorus runoff from sources such as fertilizers, fuels algal blooms. This contamination of water systems leads to the production of toxins [23].

These blooms not only compromise the safety of drinking water but also generate harmful toxins that make swimming and boating unsafe. As a result, tourism and local businesses are negatively affected [24]. According to [25], there is increasing scientific interest in investigating excessive deposition and removal of phosphorus due to its potential environmental and ecological consequences.

During the full-article screening, the removed articles primarily focused on agricultural soil studies and had incorrect outcomes. As opinioned by [26], the rigorous screening process of articles underscores the importance of including only relevant and reliable literature in the study.

The included articles met the study's inclusion criteria and provided insights into trends, methodologies, and implications for understanding the effects of PSB on PS in various water ecosystems worldwide. Table 2 summarizes the data extracted from the ten (10) selected studies.

Table 2: Data extracted from the ten (10) selected studies

Study	Ecosystem	Phosphorous form	PSI range (cm)	PSP range (mg/L)	pH reduced	PSB strain	PSB's range of PSI (cm) efficiency	PSB's range of PSP (mg/L) efficiency
Dastager& Damare, (2013)	Island	Inorganic	0.9 - 2.2	89.3 - 164.1.	3.0 - 4.5	*Streptomyces spp.Microbacteriumspp.Angustibacterspp. Kocuriaspp. Isoptericolaspp. Agromycesspp.*	*Kocuria palustris (2.3 cm Streptomyces violascens, Streptomyces cinereorectus&Angustibacter luteus (0.9 cm).*	*Kocuria palustris (164.1mg/L) & Streptomyces violascens (89.3 mg/L)*
Dipak & Sinha, (2013)	River	Inorganic	1.0 – 1.3	113.72 - 144.4.	4.17- 4.83	*Bacillus spp. Pseudomonas spp. Flavobacterium spp. Enterobacter aeromonas*	*Pseudomonas sp.(1.3 cm) &Flavobacterium sp.(1.0 cm).*	*Pseudomonas sp. (144.4 mg/L) & Flavobacterium sp. (113.72 mg/L).*
Paul & Sinha, (2015)	River	Inorganic	2.50 - 3.14	185.76 - 208.18	3.53 -5.26	*Bacillus spp.*	*Bacillus subtilis (3.14 cm) &Bacillus cereus (2.50 cm)*	*Bacillus subtilis (208.18 mg/L) & Bacilluscereus (185.76 mg/L)*
Teymouri et al. (2016)	Mangrove	Inorganic	2.3 - 3.5	215.0 - 356.0	5.2 - 6.3	*Bacillus spp. Pseudomonas spp. Acinetobacter spp.*	*Bacillus sp.(3.5 cm) &Acinetobacter sp.(2.3 cm)*	*Pseudomonas rhodesiae(356.0 mg/L) & Acinetobacter sp. (215.0 mg/L)*
Behera et al. (2017)	Mangrove	Inorganic	1.7	48.0	3.2	*Alcaligenes faecalis*	*Alcaligenes faecalis (1.7 cm)*	*Alcaligenes faecalis (48.0 mg/L).*
Paul & Sinha, (2017)	River	Inorganic	2.85	219.64	5.21	*Pseudomonas aeruginosa*	*Pseudomonasaeruginosa (2.85 cm)*	*Pseudomonas aeruginosa (219.64 mg/L)*
Teng et al. (2019)	Wetland	Organic & inorganic	1.04 -3.13	3.73 - 430.40	3.9 – 6.8	*Pseudomonas spp. Acinetobacter spp. Bacillus spp. Aeromonas spp. Enterobacter asburiae Providencia rettgeri*	*Bacillus cereus (OPSB) (3.13 cm) & Enterobacter moris AL (IPSB) (1.04 cm)*	*Enterobacter asburiae(IPSB)(430.40 mg/L) & Aeromonas sp. (OPSB) (3.73 mg/L)*
Li et al. (2019)	Lake	Inorganic	1.1 - 4.7	1.79 - 103.8	3.1 – 6.4	*Bacillus spp. Paenibacillusspp. Pseudomonas spp. Aeromonas spp.Caryophanonspp.Rhodococcusspp.Aetherivoransspp. Solibacillus, Gordoni Micromonosporahalophytica Microbacteriuminvictum*	*Bacillus idriensis(4.70 cm) & Paenibacilussp. strainFSL& Microbacteriuminvictum(1.10).*	*Bacillusidriensis (102.77 mg/L) & Paenibacillus sp. (1.79 mg/L).*
Chawngthu et al. (2020	Wetland	Inorganic	2.1 - 3.6	1.3 - 2.8	4.0 - 5.0	*Bacillus spp. Burkholderiaspp. Paenibacillusspp.*	*Paenibacillussp.(3.6 cm) & Bacillussubtilis (2.10)*	*Bacillus cereus (2.8 mg/L) & Burkholderiacenocepacia(1.3 mg/L)*
Li et al. (2022)	Lake	Organic	1.1 - 4.5	1.82 - 72.3	6.0 – 6.4	*Bacillus spp. Pseudomonas spp. Aeromonas spp. Spirosomaspp. Acidovorax spp.*	*Bacillusalbus strain N35-10-2 (4.5 cm) &Bacillusaltitudinis(1.1 cm)*	*Pseudomonas sp. (72.26mg/L) & Aeromonas veronii(1.82 mg/L)*

The PSI is an essential method for quantitatively measuring how PSB converts insoluble phosphates into a form that can be used by other living organisms in water ecosystems [27,28]. This index considers both the colony diameter and the halo zone diameter on specific media, providing an objective way to assess the effectiveness of PSB [29, 30].

According to a cited source [31], a PSI value between 1.0 and 1.5 indicates low PSI, while values between 1.5 and 4.7 indicate a moderate to strong PSI ability. A high PSI score indicates increased phosphorus release from organic and inorganic phosphate compounds, making soluble phosphorus more readily available [32,33]. Conversely, a low PSI score suggests limited PSB activity, which can harm the phosphorus cycle and productivity due to an insolubilized amount of phosphorus [34, 35].

The maximum PSI values across the PSB species (Figure 2) from the 10 selected studies indicate varying initial phosphate solubilization efficiency levels. These values range from 1.3 cm for *Pseudomonas* sp. isolated from a river ecosystem to 4.7 cm for *B. idriensis* isolated from a lake ecosystem.

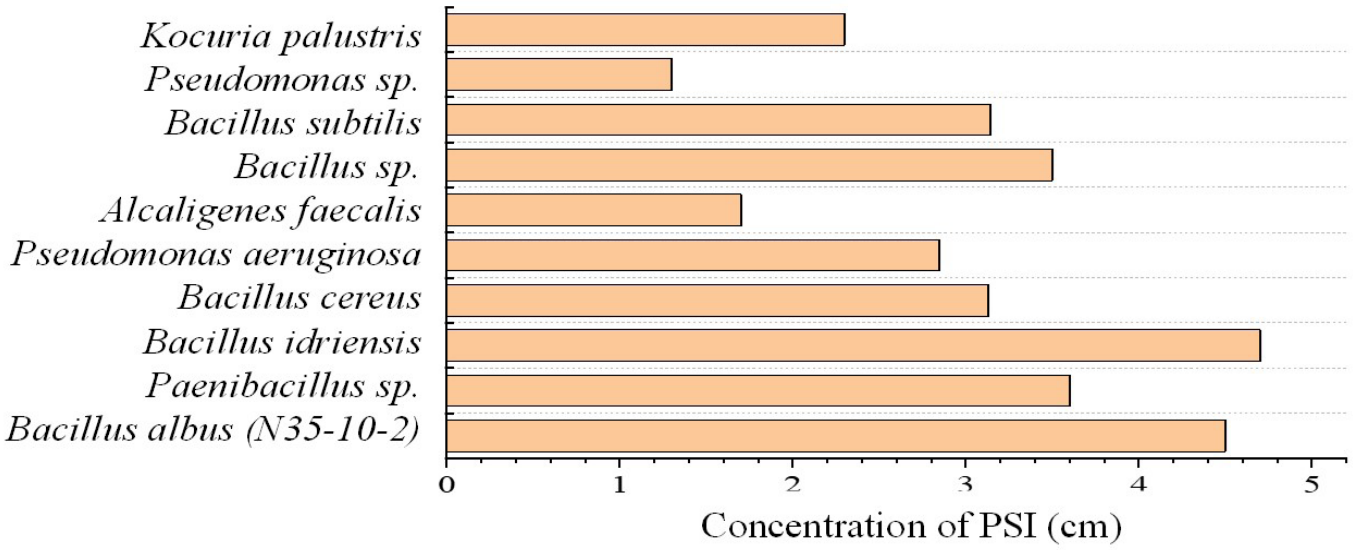


Figure 2: Maximum PSI (cm) distribution of the PSB across the ten (10) selected studies.

The range of PSI capacities among the bacterial isolates studied suggests that while certain PSB species demonstrated limited PSI activity in a particular ecosystem, others showed strong efficiency. This indicates variability within the bacterial population studied and highlights their potential functions in water ecosystems, particularly for the bioavailability of phosphorus within the ecosystems [36].

However, it has been observed in all the ecosystems analyzed that *B. idriensis* isolated from a lake has higher PSI values (4.7cm) from inorganic phosphate. The unique properties of lake environments, such as pH levels, nutrient availability, and microbial diversity, enhance *B. idriensis* ability to dissolve phosphate [37].

Research suggests that maintaining optimal pH ranges improves bacterial phosphate solubilization [38], and the specific pH conditions in the lake where *B. idriensis* was discovered likely created an ideal environment for its phosphate solubilization abilities [39].

Furthermore, specific organic compounds or carbon sources in the lake ecosystem stimulated *B. idriensis* phosphate solubilization activity [40]. [41] demonstrated that the type of carbon source available to bacteria impacts their efficiency in solubilizing phosphate. Therefore, suitable carbon sources in the lake environment contributed to higher phosphate solubilization index (PSI) values than other ecosystems.

Overtime, *B. idriensis* adaptation to the lake ecosystem resulted in genetic or metabolic changes that improved its ability to dissolve phosphate [42]. Consequently, prolonged exposure to the lake environment led to genetic adaptations in *B. idriensis*, enhancing its efficiency in phosphate solubilization [43].

Lakes typically exhibit higher PSB activity and PSI values than rivers, mangroves, islands, and wetlands [44]. This is primarily due to the more significant nutrient influx from runoff, groundwater, and atmospheric deposition sources, which stimulate PSB growth and elevate PSI values [45].

The increased nutrient availability in lakes promotes microbial activity, creating a favorable environment for the survival and activity of PSB [46]. In contrast, islands often face nutrient-deficient conditions, directly impacting the survival of PSB [47].

Human activities also play a role in microbial activity in lakes, with pollution leading to higher nutrient inputs, while less polluted islands have lower nutrient inputs [48]. In environments where phosphorus availability is limited, such as rivers, mangroves, islands, and wetlands, competition among PSB species for resources and niche space can restrict PSI activity [49].

Nutrient availability, pH levels, temperature regimes, and substrate composition strongly influence the metabolic activity and growth of PSB. Interactions among species and microbial communities further affect PSI activity [50]. Therefore, the differences in PSI values among these ecosystems can be attributed to varying nutrient inputs, microbial activities, genetic diversity, and ecosystem interactions.

The solubilization of insoluble phosphorous compounds is measured in terms of PSP (mg/L), which represents the amount of phosphorus made available by bacteria through solubilization processes [51]. PSB use various mechanisms to hydrolyze phosphate ester bonds through metabolic activity [52]. These mechanisms compete with the active site of the compounds to enhance metabolic conversion of the compounds into soluble forms, enabling the bioavailability of soluble phosphorus in water ecosystems [53].

The maximum PSP (mg/L) of the species across the ten (10) selected studies analyzed (Figure 3) varies between the ecosystems studied, with some species such as *Bacillus* and *Pseudomonas*, showing different solubilization efficiencies in the same ecosystems as mangrove, Wetland and lake, river and mangrove respectively. The efficiency of bacteria for PSP (mg/L) in water ecosystems is governed by several factors, including bacterial species diversity, nutrient availability, pH levels, temperature, presence of organic acids, competition with other microorganisms, genetic characteristics, and environmental stressors [54].

The PSP (mg/L) found among the PSB species in water in the ecosystems consistently shows high solubilizing activity. *Bacillus, Pseudomonas, Acinetobacter, E. asburiae* and *Flavobacteria* show remarkable solubilizing activity in lake, river, mangrove, Wetland and river ecosystems. This is due to the availability of nutrients within bacterial populations in the ecosystems and their ability to produce organic acids, significantly contributing to higher phosphorus solubilization. Similar findings from [55,56] emphasized that organic acids lower the pH in various water ecosystems, enhancing the bacteria's ability to solubilize insoluble phosphorus. These findings collectively underscore the crucial role of nutrient availability and acid production in the solubilization process of these bacteria.

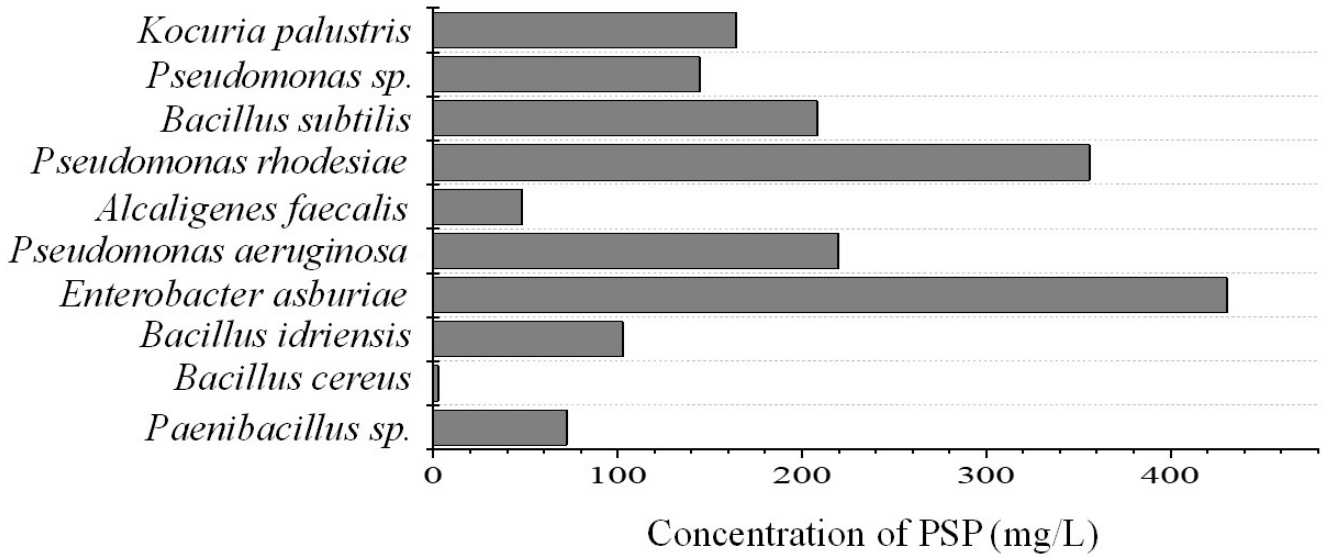


Figure 3: Maximum PSP (mg/L) distribution of the PSB across the 10 selected studies

Phosphorus-solubilizing microorganisms, such as *Bacillus, Pseudomonas, Acinetobacter, Enterobacter asburiae*, and *Flavobacteria*, play a vital role in various ecosystems such as lakes, rivers, mangroves, wetlands, and rivers by increasing the availability of phosphorus [57]. These microorganisms have been identified as efficient phosphate solubilizers, releasing organic acids into the environment that convert phosphate complexes into orthophosphate. This makes it easier for plants to access phosphorus and promotes plant growth [58]. Research has shown that PSB, including those from the genera *Bacillus, Pseudomonas, and Enterobacter,* can stimulate the release of plant root exudates, trigger plant defense mechanisms, and produce antibiotics that can inhibit diseases, ultimately benefiting plant health and growth [59].

However, *Enterobacte asburiae,* isolated from the wetland ecosystem, has been characterized by having the highest solubilization efficiency among these species. This indicates that it is essential in enhancing phosphorus availability in wetland ecosystems due to its unique abilities or specialized adaptations in solubilizing phosphate. The study by [60] reported similar findings in the Wetland of Beijing, China. Both studies highlight the significant contribution of *Enterobacte asburiae,* to phosphorus solubilization, emphasizing the species' specialized adaptations that enhance its efficiency in diverse wetland environments. A study by [61] demonstrated *Enterobacte asburiae* strain to efficiently solubilize inorganic phosphate through the secretion of gluconic acid, which is facilitated by specific enzymes such as pyrroloquinoline quinone-dependent glucose dehydrogenase. Additionally, many studies have reported that members of *Enterobacter* species can release soluble phosphorus, convert insoluble phosphates into soluble forms, optimize PS under various conditions, and significantly promote plant growth [62,63].

While most species recorded strong PSP (mg/L), some species like *Burkholderia, Aeromonas,* and *Paenibacillus,* isolated from Wetland and lake, respectively, show limited PSP (mg/L) activity. These species may possess less efficient metabolic pathways for liberating phosphorus from insoluble forms in the ecosystems. However, environmental conditions, such as temperature, pH, and nutrient availability in the ecosystems, significantly affect their ability to solubilize phosphorus [35].

Some PSB species may be more adapted to specific environmental conditions than others, which can lead to some species being competitively disadvantaged within the microbial community [64]. [65] had it that competition and adaptations of different PSB species to their environment can result in reduced solubilization activity for some strains, even if they have shown high solubilization potential in other settings. In addition, factors such as secretion of organic acids, chelation of ions, production of hydrogen sulfide (H2S) and phosphatase (Figure 4) are the essential mechanisms by which PSB solubilizes phosphate compounds [66]. The effectiveness of these mechanisms can vary among different PSB species and environmental conditions, with some species exhibiting low PSP (mg/L) in the same ecosystem.

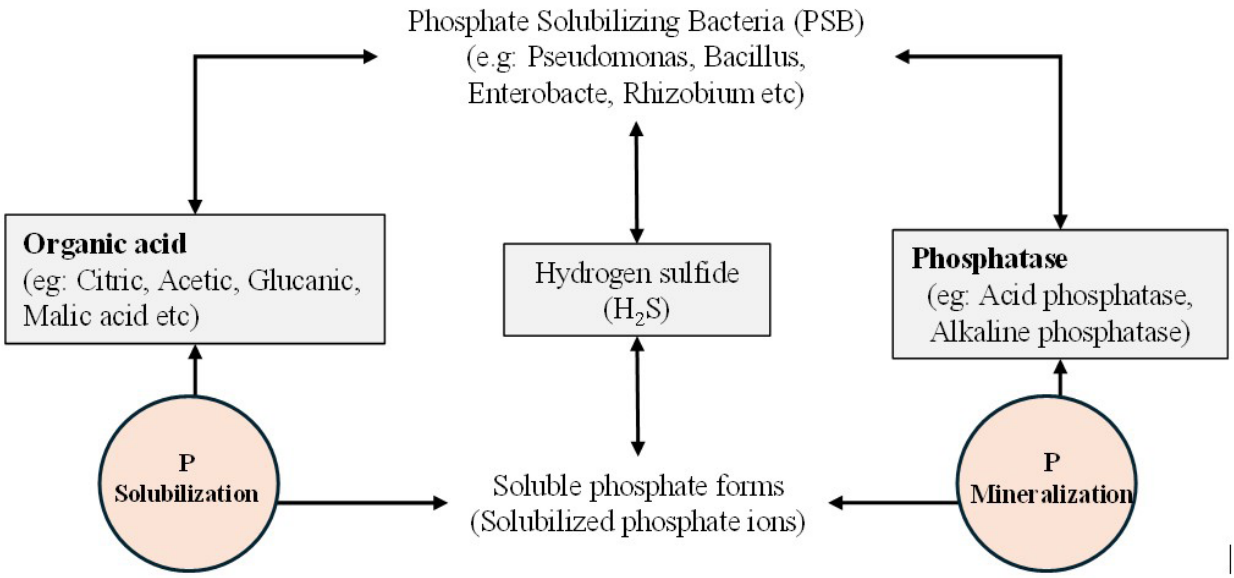


Figure 4: Schematic diagram for mechanism of bacterial phosphate solubilization

Although PSI is the primary method used to identify bacteria with phosphate solubilization capabilities, a positive PSI result indicates potential for phosphate solubilization, it does not reveal the specific mechanisms employed by the bacteria [67].

Bacterial production of organic acids or enzymes for phosphate solubilization requires significant energy investment. If readily available alternative nutrients are present, bacteria may prioritize their utilization and reduce phosphate solubilization efforts, leading to a negative PSP (mg/L) result despite a positive initial (PSI) screening [68].

Environmental factors like simple sugars, temperature, pH, and oxygen availability significantly influence bacterial behavior and their efficiency in solubilizing phosphates [69]. Competition with other microbes for resources can also affect a bacterium's decision to invest energy in phosphate solubilization [36].

While PSI serves as a valuable initial screening tool, PSP quantifies the amount of phosphate solubilized under defined conditions. This accurately represents a bacterium's ability to make phosphate available for plant uptake [70].

Therefore, combining qualitative and quantitative studies is essential for comprehensively understanding a bacterial isolate's phosphate solubilization potential. The activity of PSB in a growth medium is significantly affected by a pH reduction.

This pH reduction is made possible by the ability of PSB to produce organic acids, which is crucial for solubilizing phosphates such as tricalcium phosphate ($Ca_3(PO_4)_2$ and iron phosphate ($FePO_4$).

Figure 5 indicates the dynamic pH reduction that PSB species demonstrated during the phosphate compounds' solubilization on a growth medium.

This pH reduction enhances the solubility of otherwise insoluble phosphate compounds, making them more readily available for uptake and utilization by aquatic organisms.

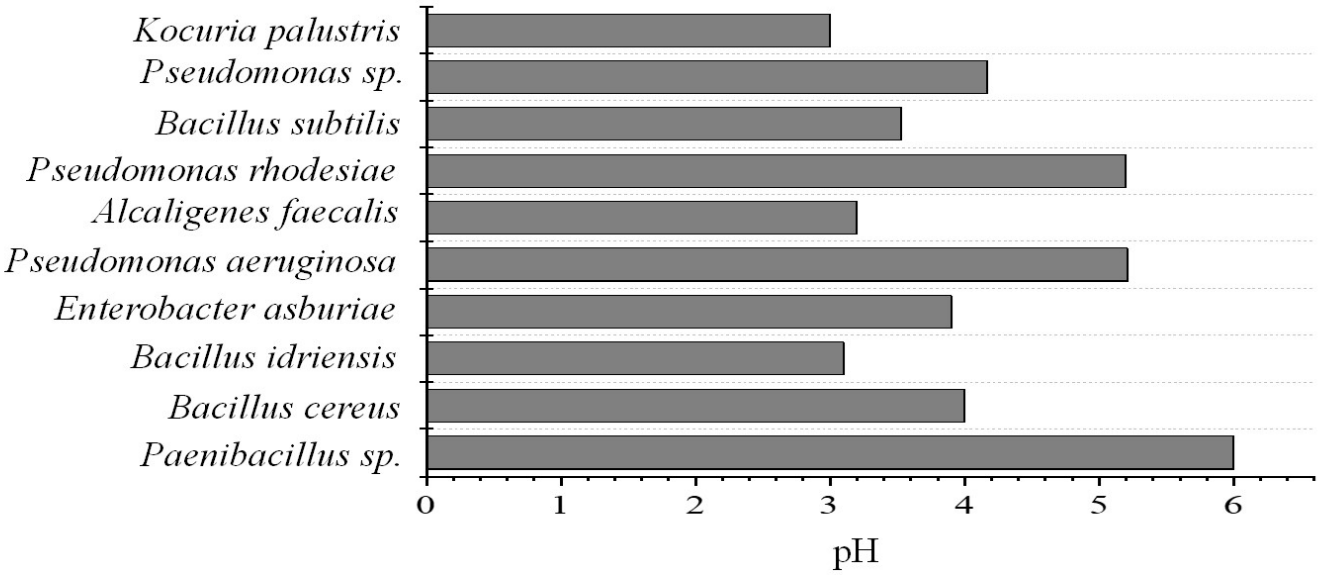


Figure 5: Maximum pH reduction distribution of the PSB across the 10 selected studies

This study observed differences in the PSB isolates analyzed to reduce pH levels for acid production. The decrease in the initial pH of 7.0±0.2, considered optimal for PSB activity, was noticeable, indicating that these bacteria effectively produce organic acids. This suggests that the primary mechanism for PS occurs through the acidification of the culture supernatants [71]. PSB require acidic conditions to effectively solubilize phosphates due to their capacity to produce organic acids as metabolic byproducts [72].

These organic acids, such as gluconic acid, citric acid, and oxalic acid, are essential to the solubilization process, as they lower the pH of the environment and facilitate the conversion of insoluble phosphates, such as tricalcium phosphate, aluminum phosphate, and iron phosphate, into forms that can be readily absorbed by living things [27]. The drop in pH caused by the organic acids disrupts the chemical bonds holding the phosphate in insoluble compounds, releasing free phosphate ions into water ecosystems [73].

Various water ecosystems like rivers, lakes, and wetlands benefit from the role of PSB in the phosphorus cycle. The activity of PSB in water ecosystems is influenced by various environmental factors, including pH, nutrient availability, microbial diversity, and ecological conditions [58]. In freshwater ecosystems, the level of nutrients affects the activity of PSB. In nutrient-rich water ecosystems, PSB can produce organic acids, thereby acidifying the environment and aiding in phosphate solubilization [53]. Anaerobic conditions in wetland ecosystems influence PSB activity through oxygen availability [74]. Although some PSB are more effective under aerobic conditions, certain anaerobic bacteria can also contribute to phosphate solubilization through different metabolic pathways [75].

The rich organic matter in wetlands is a carbon source for PSB, enhancing phosphate solubilization through producing organic acids [76]. In general, the PSB species were able to cause around 80% significant decrease in pH (below 5) during PS, indicating their potential for releasing phosphate ions into aquatic environments for phosphate management and cycling. However, certain PSB strains like Aeromonas species, Paenibacillus, Pseudomonasrhodesiae, A.veronii, and Pseudomonas species were only able to lower pH by small amounts (> 6) with low solubilization capacities.

According to [77], different bacterial strains exhibit varying pH reduction efficiencies in solubilizing insoluble phosphates, with some strains being more effective under specific conditions such as pH, temperature, nutrients, etc. Additionally, organic acids like phthalic acid have been identified as a potential mechanism for reducing pH [78]. Therefore, lower PS rates may indicate slower pH reduction during certain metabolic phases, highlighting the dynamic nature of phosphate-solubilizing processes in bacteria [79].

While some bacteria excel at rapidly producing organic acids that lower pH, others take a more gradual approach. These acids play a crucial role in reducing the pH of the medium, which enables reactions with insoluble

phosphate, converting it into a soluble form [80]. This relationship between pH and soluble phosphorus concentration indicates that lowering the pH of the medium can indeed facilitate the solubilization of insoluble phosphate [81].

Managing phosphates in water ecosystems involves controlling phosphate inputs and promoting natural solubilization without excessive nutrient loading [82]. One primary concern is eutrophication, which is caused by an excess of phosphorus and leads to the growth of algal blooms, hypoxia, and water quality degradation [83]. Bioremediation using PSB can help mitigate eutrophication by enhancing phosphate solubilization and uptake while minimizing nutrient excess in water ecosystems [54].

Additionally, managing sediments in water ecosystems effectively is vital for preventing disturbance and erosion, which can lead to the release of bound phosphates into bodies of water [84]. According to [85], stabilizing sediment and reducing erosion through practices like maintaining vegetation cover and using erosion control structures can prevent the mobilization of securely held phosphates in the sediment.

In agriculture settings, best management practices include using buffer strips to filter runoff, controlled-release fertilizers to limit excess phosphate, and conservation tillage to reduce erosion [86]. Efficient irrigation management and crop rotation also contribute to soil health and minimize phosphate runoff, thus protecting water ecosystems [87].

In industrial settings, advanced wastewater treatments such as biological phosphorus removal and membrane filtration, source reduction through material substitution and process optimization, and internal recycling systems like wastewater recycling and byproduct recovery are required [88,89]. In urban areas, preventing phosphate runoff involves using phosphate-free detergents, maintaining green infrastructure such as rain gardens and permeable pavements, properly disposing of yard waste, educating the public on reducing phosphate use, and regularly maintaining septic systems to minimize phosphate runoff into water ecosystems [90.91].

Conclusion

The study emphasizes the importance of the qualitative and quantitative methods of PS among various PSBs from the 10 selected studies. The PS activities of the species vary considerably; the diverse PS capacities among species reflect the complex microbial dynamics influenced by factors such as nutrient availability, pH levels, and microbial interactions within the ecosystems. The variations in organic acid production and pH reduction among PSB species indicate different solubilization activities, with some species efficiently producing higher PS ability. In contrast, others exhibit lower rates of PS. In addition, the use of PSB, such as *E. asburiae, B. subtilis, B. ceureus,* and *P. aeruginosa,* can help maintain effective phosphorus management and the health of water ecosystems.

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