



PESTICIDE RESISTANCE AND PHOSPHATASE ACTIVITY OF PHOSPHATE-SOLUBILIZING BACTERIA IN ACIDIC SOIL

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ABSTRACT

Phosphorus (P) is an essential macronutrient for plant growth, but its availability in soil is frequently limited by chemical fixation and conversion into poorly soluble mineral and organic forms. The problem is particularly important in acidic soils, where phosphorus is strongly associated with iron and aluminium compounds. Soil microorganisms, especially phosphate-solubilizing bacteria (PSB), contribute to phosphorus cycling by dissolving inorganic phosphate minerals and mineralizing organic phosphorus through phosphatase enzymes. At the same time, agricultural soils may receive repeated pesticide applications that can affect non-target microbial populations and their metabolic activities. Consequently, the selection of phosphate-solubilizing bacteria capable of tolerating pesticide exposure while retaining phosphorus-mobilizing functions has potential importance for sustainable agriculture. The present research paper examines the relationship between pesticide tolerance, phosphate solubilization and phosphatase activity of phosphate-solubilizing bacteria associated with acidic soil. The proposed methodology involves isolation of phosphate-solubilizing bacteria from acidic agricultural soil, qualitative and quantitative phosphate-solubilization assays, pesticide-tolerance screening, acid and alkaline phosphatase assays, biochemical characterization. The acid phosphatase activity harbouring bacterial communities can be particularly important in acidic soils, while pesticide tolerance varies substantially among bacterial isolates. The model results presented in this paper demonstrate how multifunctional isolates could be identified based on simultaneous pesticide tolerance, phosphate-solubilizing efficiency and phosphatase activity. Such isolates may have potential as microbial inoculants for phosphorus-deficient acidic soils subjected to pesticide management.

KEYWORDS: Acidic soil, Phosphate-solubilizing bacteria, Pesticide tolerance, Phosphatase, Phosphorus cycling, Bio fertilizer.

1. INTRODUCTION

Phosphorus is one of the major mineral nutrients required for biological growth and development. It participates in nucleic-acid synthesis, adenosine tri phosphate-dependent energy transfer, membrane metabolism and several enzymatic processes. Despite the relatively large quantity of total phosphorus present in many soils, only a small proportion is readily available to plants because phosphorus is converted into relatively insoluble inorganic and organic forms. Consequently, microorganisms that participate in phosphorus transformation represent an important component of soil fertility and plant nutrition (Richardson & Simpson, 2011).

The availability of phosphorus is strongly influenced by soil properties, particularly pH, mineralogy, organic matter and microbial activity. In acidic soils, phosphorus is

commonly associated with iron and aluminium minerals, reducing the amount of phosphate available for plant uptake. This makes phosphorus deficiency an important limitation to crop productivity in many acidic agricultural soils (Zheng *et al.*, 2019). A recent investigation of indigenous phosphate-solubilizing bacteria from acidic soils of north eastern India demonstrated that selected bacterial strains could solubilize insoluble phosphorus and improve phosphorus uptake and dry-matter accumulation in green gram, emphasizing the potential value of locally adapted phosphate-solubilizing bacteria for acid-soil management (Sen *et al.*, 2024).

Phosphate solubilizing bacteria constitute an important functional group of plant-growth-promoting microorganisms. Species belonging to genera such as *Pseudomonas*, *Bacillus*, *Rhizobium*, *Enterobacter* and

Serratia have been reported to possess phosphate solubilizing capabilities (Rodríguez & Fraga, 1999; Bhattacharyya & Jha, 2012). These bacteria can increase phosphorus availability through several mechanisms, including organic-acid production, proton release, chelation and enzymatic mineralization of organic phosphorus (Glick, 2012; Rodríguez & Fraga, 1999).

Phosphate mineralization represents a second major microbial mechanism of phosphorus mobilization. Organic phosphorus compounds can be hydrolysed by phosphatases, releasing inorganic orthophosphate. Acid and alkaline phosphatases have different biochemical optima, and their relative importance is influenced by environmental pH and soil conditions (Rodríguez & Fraga, 1999; Fraser *et al.*, 2017). In acidic soil, acid phosphatase activity may be particularly important for phosphorus acquisition.

The agricultural environment in which phosphate solubilizing bacteria are expected to function may also contain pesticides. Pesticides are applied to control weeds, insects and plant pathogens, but their effects are not necessarily restricted to target organisms. Soil bacteria can respond differently to pesticide exposure depending on pesticide chemistry, concentration, exposure duration and bacterial genotype. Beneficial soil bacteria recovered from pesticide-contaminated rhizospheres have demonstrated substantial variation in pesticide tolerance (2022 study).

The relationship between pesticide exposure and phosphate solubilization is particularly relevant. Ramani *et al.* (2011) examined the effects of several pesticides on phosphate-solubilizing *Bacillus sphaericus* and *Pseudomonas cepacia*, demonstrating that pesticide exposure can influence the performance of phosphate solubilizing bacteria. Such observations suggest that screening bacterial inoculants exclusively for phosphate-solubilizing ability may be insufficient for agricultural application where pesticides are routinely used.

Pesticide tolerance should, however, be distinguished from pesticide degradation. Growth of a bacterial isolate in the presence of a pesticide demonstrates tolerance under the tested conditions but does not establish that the organism metabolizes or removes the pesticide. Evidence of degradation requires chemical measurements of pesticide disappearance and, ideally, identification of transformation products. This distinction is important when interpreting bacterial responses in pesticide-contaminated soil.

The selection of multifunctional phosphate solubilizing bacteria therefore represents an important research direction. An ideal strain should tolerate the relevant acidic soil environment, maintain phosphate-solubilizing activity, produce phosphatases and ideally possess additional plant-growth-promoting characteristics. Such strains could contribute to phosphorus-use efficiency and

microbial soil health while remaining functional under pesticide-management regimes.

2. REVIEW OF LITERATURE

2.1 Phosphate-solubilizing bacteria

Phosphate-solubilizing microorganisms have been investigated for several decades as potential biological alternatives or supplements to chemical phosphorus fertilizers. Rodríguez and Fraga (1999) reported that *Pseudomonas*, *Bacillus* and *Rhizobium* include some of the important bacterial groups capable of phosphate solubilization. Their review also emphasized that organic-acid production is a major mechanism of mineral phosphate solubilization, while phosphatases contribute to organic-phosphorus mineralization.

Richardson and Simpson (2011) emphasized that microorganisms are integral components of the soil phosphorus cycle. Microbial biomass can act as both a temporary sink and a source of phosphorus, while microbial enzymes and metabolic processes determine the transformation of phosphorus between different pools. Therefore, manipulating beneficial microorganisms may provide an opportunity to increase phosphorus availability without relying entirely on increased fertilizer application.

The development of NBRIP medium by Nautiyal (1999) improved laboratory screening of phosphate-solubilizing microorganisms. The author demonstrated that liquid NBRIP medium could provide greater recovery of phosphate-solubilizing activity than conventional screening approaches and warned that absence of a visible halo on agar does not necessarily mean that an isolate lacks phosphate-solubilizing capacity. Consequently, quantitative broth assays should complement plate-based screening.

More recent research confirms the importance of selecting phosphate solubilizing bacteria adapted to acidic environments. Sen *et al.* (2024) isolated phosphate solubilizing bacteria from acid soils of north eastern India and demonstrated that selected isolates could mobilize insoluble phosphorus and improve plant phosphorus uptake. These findings provide a strong rationale for investigating indigenous phosphate-solubilizing bacteria rather than relying exclusively on strains isolated from neutral soils.

2.2 Phosphatases and phosphorus mineralization

Phosphatases catalyse the hydrolysis of phosphate ester bonds and contribute to the release of inorganic phosphate from organic phosphorus compounds. Microbial phosphatases therefore represent an important biochemical mechanism linking microbial activity with plant phosphorus availability (Richardson & Simpson, 2011).

Research involving *Serratia* further illustrates the potential for simultaneous phosphate solubilization and

phosphatase production. Behera *et al.* (2017) isolated a *Serratia* strain from mangrove soil that demonstrated phosphate-solubilizing activity accompanied by acid phosphatase production. The study supports the concept that a single bacterial isolate can employ both mineral phosphate dissolution and organic-phosphorus mineralization.

2.3 Acidic soil and phosphorus limitation

Acidic soils are often characterized by low pH and substantial phosphorus fixation. In such environments, phosphorus can become associated with aluminium and iron compounds, limiting its availability to plants. The effectiveness of phosphate-solubilizing bacteria may consequently depend on their ability to remain metabolically active at low pH and to mobilize phosphorus under these chemical conditions (Zheng *et al.*, 2019; Sen *et al.*, 2024).

The influence of soil pH on phosphate-solubilizing bacteria performance is important because many laboratory screening studies are conducted under neutral or near-neutral conditions. A meta-analysis by De Zutter *et al.*, (2022) emphasized that the effectiveness of phosphate-solubilizing bacteria inoculation is influenced by soil pH and that a substantial proportion of published screening work has been conducted under conditions that do not necessarily represent acidic agricultural soils.

Indigenous isolates may therefore offer advantages because they have already experienced the chemical and biological stresses characteristic of their native environment. Sen *et al.* (2024) demonstrated this principle by selecting phosphate-solubilizing bacteria from acid soils and showing that selected strains could increase phosphorus use efficiency and plant phosphorus acquisition.

2.4 Pesticide tolerance of soil bacteria

Pesticides can affect microbial communities directly through toxicity or indirectly by altering nutrient availability and microbial interactions. However, bacterial responses vary considerably. Some microorganisms are sensitive to pesticide exposure, whereas others can tolerate or transform specific compounds.

Ramani *et al.* (2011) investigated pesticide effects on phosphate solubilization by *Bacillus sphaericus* and *Pseudomonas cepacia*. Their work is particularly relevant because it demonstrates that pesticide exposure should be considered when evaluating phosphate-solubilizing bacteria for real agricultural applications.

More recent research involving beneficial bacteria from pesticide-contaminated rhizospheres found considerable variation in tolerance among bacterial isolates. The study included phosphate-solubilizing bacteria and demonstrated that pesticide tolerance was isolate-dependent (2022 study). This supports the hypothesis that

selecting tolerant strains from agricultural soils may identify bacterial candidates better suited to pesticide-managed environments.

Nevertheless, pesticide tolerance alone does not demonstrate ecological superiority. A strain may survive pesticide exposure while losing its phosphate-solubilizing or phosphatase-producing activity. Therefore, simultaneous functional screening is necessary.

3. OBJECTIVES OF THE STUDY

The objectives of the proposed investigation are:

1. To isolate phosphate-solubilizing bacteria from acidic agricultural soil.
2. To determine the physicochemical characteristics of the soil.
3. To screen bacterial isolates for qualitative phosphate solubilization.
4. To quantify phosphate-solubilization efficiency.
5. To evaluate bacterial tolerance to selected agricultural pesticides.
6. To determine acid and alkaline phosphatase activity.
7. To examine the effect of pesticide exposure on phosphate solubilization.
8. To identify superior multifunctional phosphate-solubilizing bacteria isolates.
9. To investigate relationships between pesticide tolerance, phosphate solubilization and phosphatase activity.
10. To propose promising isolates for future bio fertilizer and sustainable soil-management studies.

4. MATERIALS AND METHODS

4.1 Soil sampling

Acidic agricultural soil should be collected from cultivated fields with a known history of pesticide use. Samples should preferably be collected from the rhizosphere because plant roots provide carbon compounds that support metabolically active microbial communities. Soil sampling should be performed aseptically using sterile tools, and samples should be transported under suitable conditions for microbiological analysis.

The soil pH should be determined before bacterial isolation. Acidic sites may be classified according to established soil-pH categories, with particular emphasis on samples below approximately pH 6.0.

4.2 Physicochemical analysis

Soil pH should be determined using a calibrated pH meter. Electrical conductivity, organic carbon, available nitrogen and available phosphorus should be determined using standardized soil analytical procedures.

Available phosphorus is particularly important because microbial phosphatase activity and phosphorus-cycling communities can respond to soil phosphorus status (Zheng *et al.*, 2019; Fraser *et al.*, 2015).

Table 1: Proposed soil parameters.

Parameter	Analytical method	Importance
pH	Electrometric method	Determines acidity
Electrical conductivity	Conductivity meter	Indicates soluble salts
Organic carbon	Standard oxidation method	Indicates carbon availability
Available phosphorus	Appropriate soil-P extraction	Indicates plant-available P
Total phosphorus	Digestion/colorimetric method	Total P pool
Available nitrogen	Standard soil-N method	Nutrient status
Moisture	Gravimetric method	Microbial activity

4.3 Isolation of phosphate-solubilizing bacteria

Serial dilution of soil suspensions should be performed using sterile physiological saline or an appropriate diluent. Aliquots should be inoculated onto Pikovskaya's agar or NBRIP agar. Plates should be incubated under conditions appropriate for the target bacterial population.

Colonies producing visible phosphate-solubilization zones should be purified through repeated streaking. Pure cultures should be maintained on suitable media and stored appropriately for subsequent analysis.

NBRIP medium is particularly useful because Nautiyal (1999) demonstrated that broth-based NBRIP screening can detect phosphate-solubilizing activity that may not be apparent from agar halo formation alone.

4.4 Phosphate-solubilization index

The phosphate-solubilization index can be calculated using:

$$\text{PSI} = \frac{\text{Total colony} + \text{halo diameter}}{\text{Colony diameter}}$$

Three independent replicates should be performed for each isolate.

Table 2: Illustrative qualitative phosphate-solubilization results.

Isolate	Halo diameter (mm)	PSI	Interpretation
PSB-1	7.2 ± 0.4	2.44	High
PSB-2	5.1 ± 0.3	2.02	Moderate
PSB-3	8.5 ± 0.5	2.70	Very high
PSB-4	4.4 ± 0.2	1.88	Moderate
PSB-5	6.8 ± 0.4	2.36	High
PSB-6	3.8 ± 0.3	1.76	Low

4.5 Quantitative phosphate solubilization

Selected isolates should be inoculated into liquid NBRIP medium containing an insoluble phosphate source. Following incubation, bacterial cells should be removed through centrifugation and soluble phosphorus quantified using a suitable colorimetric procedure.

The final pH should also be measured because acidification may contribute to phosphate solubilization. However, pH decline should not be considered proof of a single mechanism because chelation, enzymatic activity and other metabolic processes can contribute to phosphate mobilization (Glick, 2012; Pan & Cai, 2023).

Table 3: Illustrative quantitative phosphate-solubilization results.

Isolate	Soluble P (mg L ⁻¹)	Final pH
PSB-1	118.4 ± 5.7	4.21
PSB-2	79.6 ± 4.3	4.67
PSB-3	146.8 ± 6.2	3.98
PSB-4	65.2 ± 3.9	4.81
PSB-5	127.3 ± 5.1	4.13
PSB-6	52.7 ± 3.1	5.03

4.6. Pesticide-tolerance assay

The pesticide-tolerance experiment should use pesticides relevant to the agricultural field from which the bacterial isolates were obtained. The assay should include an untreated control and a series of pesticide concentrations.

Growth may be measured by optical density, colony-forming units or another validated bacterial-growth indicator. The percentage inhibition can be calculated as:

$$\text{Percentage inhibition} = \frac{[(\text{Control growth} - \text{Treatment growth}) / \text{Control growth}] \times 100}{1}$$

The minimum inhibitory concentration may also be determined where appropriate.

The terminology used should preferably be pesticide tolerance unless the experiment establishes a formal resistance phenotype. This distinction is scientifically

important because bacterial growth in the presence of a chemical does not automatically demonstrate a genetic resistance mechanism.

Table 4: Illustrative pesticide-tolerance results.

Isolate	Control	Low concentration	Medium concentration	High concentration
PSB-1	100	96	87	68
PSB-2	100	91	70	42
PSB-3	100	98	91	76
PSB-4	100	86	61	30
PSB-5	100	95	84	64
PSB-6	100	82	55	24

Note: Values represent illustrative percentage growth relative to untreated controls.

The model results indicate that PSB-3 has the greatest tolerance at increasing pesticide concentrations. Such a result would justify selecting PSB-3 for additional functional testing if it were confirmed experimentally.

Acid phosphatase activity is particularly relevant to the present research because the study focuses on acidic soils. Zheng *et al.* (2019) reported higher acid phosphatase activity than alkaline phosphatase activity in the acidic soils investigated, together with a positive association between acid phosphatase activity and *phoC* abundance.

4.7 Phosphatase activity

Acid and alkaline phosphatase activity can be estimated using *p*-nitrophenyl phosphate as a substrate. The production of *p*-nitrophenol can be measured spectrophotometrically.

Table 5: Illustrative phosphatase activity.

Isolate	Acid phosphatase (U mL ⁻¹)	Alkaline phosphatase (U mL ⁻¹)
PSB-1	61.4 ± 2.8	32.7 ± 2.1
PSB-2	42.6 ± 2.4	28.9 ± 1.8
PSB-3	78.6 ± 3.5	38.4 ± 2.2
PSB-4	36.8 ± 1.9	25.1 ± 1.6
PSB-5	69.2 ± 3.0	35.7 ± 2.0
PSB-6	29.7 ± 1.7	22.6 ± 1.5

Note: Illustrative values only.

The model dataset suggests that PSB-3 exhibits the highest acid phosphatase activity. If experimentally confirmed, this isolate would be particularly interesting because it combines high phosphate solubilization with high acid phosphatase activity.

by maintenance of phosphorus-mobilizing function. This is important because a bacterium that survives pesticide exposure but loses phosphate-solubilizing activity would have limited value as a multifunctional bio fertilizer.

4.8 Effect of pesticide exposure on phosphate solubilization

A major component of the proposed investigation is determining whether pesticide tolerance is accompanied

Table 6: Illustrative effect of pesticide exposure on soluble phosphorus.

Isolate	Control	Low dose	Medium dose	High dose
PSB-1	118.4	114.1	103.7	82.6
PSB-2	79.6	73.4	60.8	41.5
PSB-3	146.8	143.2	133.5	119.7
PSB-4	65.2	57.9	43.8	31.1
PSB-5	127.3	121.8	108.6	91.3
PSB-6	52.7	46.2	34.5	22.8

in soil because of differences in carbon availability, pH and mineral composition (Nautiyal, 1999).

Third, pesticide tolerance assays should be interpreted carefully. Survival at a pesticide concentration demonstrates tolerance under experimental conditions but does not necessarily demonstrate degradation or genetic resistance.

Fourth, phosphatase activity is strongly influenced by assay conditions such as pH, temperature, and substrate concentration and incubation time. Standardized procedures The model indicates that PSB-3 retains the greatest phosphate-solubilizing capacity under pesticide exposure. This type of response would be desirable in agricultural systems where pesticides are used during crop production.

Ramani *et al.* (2011) demonstrated that pesticide exposure can influence phosphate solubilization in bacterial strains, supporting the need to evaluate this interaction experimentally rather than assuming that phosphate-solubilizing activity will remain unchanged.

5. DISCUSSION

The major objective of the present research framework is to identify phosphate-solubilizing bacteria that can maintain phosphorus-mobilizing activity under pesticide stress in acidic soil. This approach is more agriculturally relevant than evaluating phosphate solubilization alone because bacterial inoculants are expected to function in complex environments containing multiple chemical and biological stresses.

The importance of phosphate-solubilizing bacteria in phosphorus cycling is well established. Microorganisms can mobilize phosphorus through both inorganic phosphate dissolution and organic-phosphorus mineralization (Richardson & Simpson, 2011; Rodríguez & Fraga, 1999). Organic-acid production is particularly important for mineral phosphate solubilization, while phosphatases contribute to the release of inorganic phosphate from organic phosphorus compounds (Glick, 2012).

Acidic soil provides a particularly important environment for this process. Phosphorus fixation by iron and aluminium can reduce the availability of phosphate to crops. Consequently, bacteria capable of functioning at low pH and mobilizing fixed phosphorus may have a practical advantage in acid-soil agriculture (Zheng *et al.*, 2019; Sen *et al.*, 2024).

The illustrative results presented in this paper identify PSB-3 as the strongest multifunctional candidate. The isolate demonstrates high phosphate-solubilizing index (PSI), high soluble-phosphate release, strong acid phosphatase activity and comparatively high pesticide tolerance. If similar results were obtained experimentally, PSB-3 would warrant detailed molecular characterization and greenhouse testing.

Nautiyal (1999) demonstrated that agar halo formation alone may not accurately identify the most efficient phosphate-solubilizing microorganisms. This observation has direct relevance to the present methodology. A strain with a modest halo may still release substantial quantities of soluble phosphorus in liquid culture.

The relationship between pesticide exposure and bacterial phosphate solubilization is more complex. Pesticides can alter microbial growth and metabolism, but the response is dependent on the organism and chemical compound. Ramani *et al.* (2011) demonstrated that pesticide exposure influenced phosphate-solubilizing bacterial performance, supporting the need to screen phosphate-solubilizing bacteria under pesticide stress.

The model results show a gradual decline in phosphate solubilization with increasing pesticide concentration. Such a pattern would be biologically reasonable, but it should not be generalized without experimental verification. Bacterial responses may differ substantially between pesticides, and low concentrations can produce responses that are different from those observed at high concentrations.

Recent evidence indicates considerable variation in pesticide tolerance among beneficial soil bacteria. A study of isolates from pesticide-contaminated crop rhizospheres reported variable agrochemical tolerance among phosphate-solubilizing bacteria and other beneficial bacterial groups (2022 study). This variability provides a rationale for screening several independent isolates rather than relying on a single bacterial strain.

Pesticide tolerance may arise through several mechanisms, including reduced chemical uptake, efflux systems, extracellular polymer production, and enzymatic transformation and stress-response pathways. However, demonstration of tolerance does not establish the specific mechanism. Molecular and chemical analyses would therefore be necessary to investigate the basis of tolerance.

An important distinction should also be made between pesticide tolerance and pesticide degradation. A bacterial isolate that grows in pesticide-containing medium may simply withstand the chemical. If degradation is claimed, pesticide concentrations must be measured over time using an appropriate analytical technique such as HPLC, GC-MS or LC-MS.

The possibility of selecting bacteria with both phosphorus-mobilizing and pesticide-transforming functions is scientifically attractive. Such organisms could potentially contribute simultaneously to nutrient acquisition and reduction of pesticide residues. Nevertheless, this possibility requires experimental verification and should not be assumed solely from growth under pesticide exposure.

The rhizosphere provides another important consideration. Plant roots release organic compounds that can stimulate microbial activity and influence soil pH. Plant-growth-promoting rhizobacteria can enhance plant performance through phosphate solubilization, hormone production, siderophore synthesis and other mechanisms (Bhattacharyya & Jha, 2012). Therefore, the ultimate value of a phosphate-solubilizing bacteria isolate should be tested in association with plants rather than inferred solely from culture-medium experiments.

Recent work in acidic Indian soils provides encouraging evidence for this approach. Sen *et al.* (2024) isolated indigenous phosphate-solubilizing bacteria and demonstrated that selected strains improved phosphorus uptake and dry-matter accumulation in green gram. Such studies demonstrate the importance of progressing from in vitro screening to plant-based validation.

The ecological effectiveness of phosphate-solubilizing bacteria is also influenced by soil pH. De Zutter *et al.*, (2022) found that the effectiveness of phosphate-solubilizing bacteria inoculation varied with soil conditions, highlighting the importance of environmental compatibility. Therefore, selecting bacteria from acidic soils may improve the likelihood of successful establishment in similarly acidic agricultural environments.

The present study also has implications for phosphorus-use efficiency. Chemical phosphorus fertilizer can become fixed in soil, reducing fertilizer-use efficiency. Microbial mobilization of fixed phosphorus may improve the effectiveness of existing soil phosphorus pools and potentially reduce the requirement for excessive fertilizer inputs (Richardson & Simpson, 2011).

The use of multifunctional bacterial inoculants should therefore be considered as part of integrated nutrient management rather than as a complete replacement for mineral fertilizer. Field performance depends on microbial survival, root colonization, soil chemistry, crop genotype, environmental conditions and interactions with native microbial communities.

6. LIMITATIONS

The first major limitation is that laboratory experiments cannot completely reproduce field conditions. Soil texture, organic matter, moisture, temperature, pesticide adsorption and interactions with native microorganisms can influence bacterial performance.

Second, phosphate-solubilization results obtained in culture media may not directly predict field performance. A bacterial isolate that performs strongly in NBRIP broth may behave differently are therefore essential for comparisons among isolates.

7. FUTURE RESEARCH

Future investigations should include 16S rRNA sequencing of the most promising isolates. This would establish accurate taxonomic identity and facilitate comparison with previously characterized phosphate-solubilizing bacteria.

Pesticide degradation should also be examined chemically. If a bacterial isolate demonstrates strong tolerance, pesticide concentrations should be measured before and after incubation. Identification of transformation products would provide stronger evidence of biodegradation.

Greenhouse experiments should subsequently evaluate the effects of selected phosphate-solubilizing bacteria on plant growth, phosphorus uptake, soil available phosphorus and pesticide residue dynamics. A suitable crop should be selected according to the source agricultural system.

Finally, field experiments should compare phosphate-solubilizing bacteria inoculation with conventional fertilizer management and integrated treatments. Such experiments would establish whether laboratory-selected bacteria can survive, colonize plant roots and improve phosphorus-use efficiency under real agricultural conditions.

8. CONCLUSIONS

Phosphate-solubilizing bacteria represent an important microbial resource for improving phosphorus availability in acidic agricultural soils. Their importance arises from their capacity to dissolve poorly soluble inorganic phosphates and mineralize organic phosphorus through phosphatase enzymes (Rodríguez & Fraga, 1999; Richardson & Simpson, 2011).

Acidic soils present particular challenges because phosphorus can be strongly associated with iron and aluminium compounds. Consequently, indigenous phosphate-solubilizing bacteria adapted to low-pH conditions may represent promising candidates for biological phosphorus mobilization (Zheng *et al.*, 2019; Sen *et al.*, 2024).

Pesticide exposure introduces an additional selection pressure. Because bacterial tolerance to pesticides is variable, Phosphate-solubilizing bacteria intended for agricultural use should be screened for their ability to survive relevant pesticide exposure while maintaining their phosphorus-mobilizing functions (Ramani *et al.*, 2011).

The integrated selection of phosphate-solubilizing bacteria based on phosphate solubilization, phosphatase activity, acidic-pH adaptation and pesticide tolerance could therefore provide a stronger foundation for microbial bio fertilizer development than selection based on a single characteristic.

Overall, the proposed research provides a scientifically relevant framework for understanding the interaction between pesticide stress and microbial phosphorus cycling in acidic soil. The eventual identification of stable, pesticide-tolerant and phosphatase-producing phosphate-solubilizing bacteria could contribute to improved phosphorus-use efficiency and more sustainable management of acidic agricultural soils.

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Sri Saraswati Devi Hindu goddess of learning, the arts, and music. She first appears in Vedic sources, as the personification of the sacred river Saraswati, which might have been a physical river, though later texts describe it as having disappeared. As Hinduism developed, Saraswati became identified with vac, the Vedic goddess of speech, and the consort and mind-born daughter of the creator god Brahma. Hindus revere her as the patron goddess of education, the arts, music, and speech, and she is typically pictured accompanied by a goose or swan while holding a manuscript and her signature veena.



Murugan Sri Ram

Murugan Sri Ram is a microbiologist and author dedicated to bridging the gap between academic theory and industrial application. With an M.Phil. in Microbiology from Manonmaniam Sundaranar University, he has served as both an Assistant Professor and a Department Head. He is the author of *The Native Profile of Common Gram-negative Bacterial Pathogens* and has published extensively in international journals. Based in India, Murugan Sri Ram is currently exploring the evolving landscape of microbial resistance in industrial environments.