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CHAPTER 2

Microbial Phosphorus Mobilization and Alkaliphilic Actinobacteria for Sustainable Agriculture: Mechanisms, Bioinoculant Development and Future Perspectives

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Abstract: Sustainable agriculture requires nutrient-management systems that improve crop productivity while reducing inefficient resource use and environmental losses. Phosphorus (P) is indispensable for ATP-mediated energy transfer, nucleic-acid synthesis, membrane metabolism, photosynthesis and plant development, yet much of the phosphorus present in soil is poorly available because it is strongly sorbed or precipitated in mineral forms. Phosphate-solubilizing and phosphate-mineralizing microorganisms (PSMs) can mobilize these pools through organic-acid

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production, chelation, phosphatase and phytase activity, and interactions within the rhizosphere. This review examines microbial phosphorus mobilization with particular emphasis on alkaliphilic Actinobacteria and Arthrobacter crystallopoietes PJC-S08, a strain associated with a Microphos-type bioinoculant development concept. The supplied research framework describes alkaline enrichment of microorganisms from the Lonar Lake environment, screening for phosphate mobilization, molecular identification, enzyme characterization, process optimization, low-cost medium development, fermentation scale-up and plant-level evaluation. These stages illustrate a research-to-application pathway for converting extremophilic microbial resources into agricultural biotechnology. The review further considers formulation, biosafety, field validation, integrated nutrient management, circular bioeconomy opportunities and emerging tools such as genomics, multi-omics and precision biofertilization. The evidence indicates that microbial phosphorus technologies are best positioned as complementary components of integrated nutrient management rather than universal replacements for mineral fertilizers. (Alori et al., 2017; Richardson and Simpson, 2011; Kaur et al., 2024)

Keywords: phosphate-solubilizing microorganisms; phosphorus-use efficiency; sustainable agriculture; alkaliphilic Actinobacteria; Arthrobacter crystallopoietes; alkaline phosphatase; biofertilizer; Microphos; soil health; circular bioeconomy.

1. Introduction

Agricultural production must simultaneously address food demand, soil degradation, resource limitations and environmental protection. Nutrient-use efficiency is therefore as important as yield itself. Soil microorganisms are central to this transition because they regulate decomposition, mineral weathering, nutrient cycling and plant–microbe interactions. In phosphorus cycling, microbial activity can alter the balance between unavailable, mineral-associated and biologically accessible phosphorus pools (Richardson and Simpson, 2011; Alori et al., 2017). (Richardson and Simpson, 2011; Alori et al., 2017; Boubekri et al., 2022)

Phosphorus is an essential macronutrient involved in ATP and ADP energy transfer, nucleic-acid synthesis, phospholipid formation, photosynthetic reactions and cellular regulation. However, total soil phosphorus does not represent plant-available phosphorus. In many soils, phosphate becomes associated with calcium, iron and aluminium minerals or incorporated into organic compounds, limiting immediate plant uptake (Khan et al., 2007; Sharma et al., 2013). Consequently, repeated fertilizer application does not necessarily translate proportionally into phosphorus acquisition by crops. (Khan et al., 2007; Richardson and Simpson, 2011; Sharma et al., 2013)

PSMs provide a biological approach to this problem. Bacteria, Actinobacteria and fungi can release phosphorus through organic-acid secretion, mineral chelation, extracellular phosphatases, phytases and other biochemical processes (Rodríguez and Fraga, 1999; Alori et al., 2017). Their value is particularly relevant in sustainable agriculture because they may improve access to phosphorus already present in soil or fertilizer pools. Nevertheless, laboratory solubilization does not automatically guarantee field-level phosphorus uptake; performance depends on soil chemistry, microbial competition, plant genotype, environmental conditions and formulation quality (Kaur et al., 2024; Sun et al., 2026). (Rodríguez and Fraga, 1999; Alori et al., 2017; Kaur et al., 2024)

2. Phosphorus Availability and the Sustainability Challenge

Soil phosphorus exists in interconnected inorganic and organic pools. Inorganic phosphorus is commonly associated with calcium, iron and aluminium minerals, whereas organic phosphorus includes phosphomonoesters, phosphodiesters and phytate. Microbial communities participate in both mineralization and immobilization, thereby influencing the rate at which phosphorus becomes available to plants (Richardson and Simpson, 2011). (Richardson and Simpson, 2011; Sharma et al., 2013)

The sustainability challenge is the mismatch between phosphorus present in soil, phosphorus applied through fertilizers and phosphorus actually captured by crops. Improving phosphorus-use efficiency requires coordinated fertilizer placement and timing, recycling of organic materials, erosion control, efficient crop genotypes and biological mobilization (Khan et al., 2007; Sharma et al., 2013). Excess phosphorus entering water bodies can contribute to eutrophication, while phosphate-rock extraction, processing and transportation involve additional resource and energy requirements. Microbial technologies cannot independently resolve these issues, but they can form part of integrated systems designed to improve nutrient recovery and reduce avoidable inputs (Cheng et al., 2023). (Khan et al., 2007; Cheng et al., 2023; Lei et al., 2025)

3. Microbial Mechanisms of Phosphorus Mobilization

PSMs are taxonomically diverse and include Bacillus, Pseudomonas, Rhizobium, Enterobacter, Acinetobacter and Serratia, together with fungi such as Aspergillus and Penicillium. Actinobacteria are of special interest because many members combine metabolic versatility with tolerance to environmental stress (Boubekri et al., 2022; Santoyo et al., 2026). Organic-acid-mediated solubilization is one of the best-established mechanisms. Organic acids can decrease the pH of localized microsites and chelate calcium, iron or aluminium associated with phosphate minerals. The extent of solubilization depends on microbial strain, carbon source, phosphate substrate and

environmental conditions (Rodríguez and Fraga, 1999; Alori et al., 2017). In alkaline environments, the relevant chemistry can differ from that of acidic soils, making alkaline-adapted organisms especially interesting for targeted research. (Rodríguez and Fraga, 1999; Boubekri et al., 2022; Santoyo et al., 2026)

A second major mechanism is enzymatic mineralization of organic phosphorus. Phosphatases hydrolyse phosphate ester bonds, while phytases contribute to the release of phosphorus from phytate. Alkaline phosphatases are particularly relevant to organisms that remain active under elevated pH. Therefore, assessment of phosphorus mobilization should extend beyond the traditional halo-zone assay to include quantitative phosphate release, enzyme activity and plant phosphorus uptake (Sharma et al., 2013; Sun et al., 2026). PSMs can also promote plant growth through indole-3-acetic acid (IAA), siderophores, extracellular metabolites and stress-mitigating functions. These traits may influence root architecture, nutrient acquisition and rhizosphere interactions (Cheng et al., 2023; Kumar et al., 2025). However, multifunctionality should be experimentally verified because metabolite production in culture does not necessarily establish causation for plant responses. (Sharma et al., 2013; Alori et al., 2017; Sun et al., 2026)

4. Relevance of Alkaliphilic Actinobacteria

Alkaline soils can impose nutritional constraints because phosphorus may be present in poorly soluble mineral forms. Microorganisms adapted to high pH may have physiological characteristics that allow growth, enzyme production and persistence under conditions that restrict less-adapted microorganisms. This makes alkaline environments valuable sources for agricultural bioprospecting. (Boubekri et al., 2022; Soumare et al., 2020)

Actinobacteria are particularly attractive because of their environmental robustness and metabolic diversity. Their reported roles include nutrient cycling, plant-growth promotion and phosphorus and potassium mobilization (Boubekri et al., 2022). For bioinoculant development, however, environmental adaptation is only an initial selection criterion. A candidate strain must also demonstrate stable identity, functional activity, crop compatibility, formulation stability, biosafety and reproducible performance in realistic soils (Soumare et al., 2020; Kaur et al., 2024). (Boubekri et al., 2022; Kaur et al., 2024; Soumare et al., 2020)

5. Arthrobacter crystallopoietes PJC-S08: Research-to-Application Framework

The supplied research methodology presents a staged framework for developing an alkaliphilic microbial resource into a potential phosphorus-management technology. Environmental samples from the Lonar Lake crater vicinity were subjected to alkaline enrichment at approximately pH 9,

followed by selective isolation, phenotypic characterization, molecular identification and functional screening. The framework then progresses to enzyme purification, optimization of production parameters, cost-effective medium development, fermentation scale-up and plant evaluation (supplied research methodology). The isolation strategy included soil and sediment sampling, serial dilution and selective plating using alkaline actinomycete and modified Gauze-type media. Morphological observations were supplemented by biochemical tests, including catalase, urease, starch hydrolysis, nitrate reduction, citrate utilization, casein hydrolysis and carbohydrate utilization. This combination connects environmental isolation with phenotypic documentation. (Soumare et al., 2020; Kaur et al., 2024)

Isolate A7 was identified within the Arthrobacter lineage using 16S rRNA gene amplification, sequencing, BLAST comparison and phylogenetic analysis. The reported phosphate-solubilization index was 3.52 ± 0.07. This value is useful as a screening indicator, but it should not be treated as a direct estimate of agronomic phosphorus availability. Quantitative soluble-P measurements, enzyme assays, soil phosphorus fractions and plant phosphorus uptake provide stronger evidence for functional efficacy.The enzyme-development component included ammonium sulfate fractionation, dialysis, ion-exchange and gel-filtration chromatography, together with SDS-PAGE. Such biochemical characterization can help link phosphorus mobilization to extracellular enzyme activity. The supplied methodology further examined pH, temperature, incubation time, carbon and nitrogen sources. A cost-oriented SPG medium based on soybean meal, glucose and zinc sulfate at alkaline pH illustrates how production economics can be incorporated into sustainability-oriented biotechnology. (Kaur et al., 2024; Sharma et al., 2013)

The development pathway progressed from shake-flask culture to bioreactor production and larger-volume fermentation, followed by pot evaluation using wheat, maize and sorghum. Plant measurements included root and shoot growth and biomass-related parameters. This sequence—from discovery and identification through process development to plant testing—is important because many microbial candidates fail when laboratory performance is transferred directly to field conditions. (Soumare et al., 2020; Kaur et al., 2024)

6. Sustainability and Industrial Significance

The sustainability contribution of a Microphos-type bioinoculant can be considered across several dimensions. First, microbial mobilization may increase the fraction of poorly available phosphorus accessible to crops, potentially improving phosphorus-use efficiency. This claim must be tested through soil available-P measurements, plant P uptake and agronomic efficiency rather than inferred from microbial growth alone. Second, effective inoculants may complement mineral

fertilizer and improve synchronization between phosphorus supply and crop demand. Reduced fertilizer use should not be assumed; it must be demonstrated through multi-rate fertilizer × inoculant experiments with appropriate controls. Third, microbial technologies may contribute to soil biological functioning through interactions with native rhizosphere communities, although repeated-season microbiome and soil-enzyme measurements are needed. (Alori et al., 2017; Cheng et al., 2023; Kaur et al., 2024)

Fourth, the use of inexpensive renewable or agro-industrial substrates for fermentation may support a circular bioeconomy. Low-cost substrates can potentially reduce production costs, but sustainability should be evaluated using life-cycle and techno-economic approaches. Energy use for sterilization and aeration, water consumption, downstream processing, packaging and transportation should be included. (Cheng et al., 2023; Lei et al., 2025)

7. Formulation, Scale-Up and Field Validation

A phosphorus-solubilizing phenotype is not equivalent to a commercial biofertilizer. Formulation is a major transition point between laboratory discovery and agricultural use. Carrier selection, viable cell concentration, water activity, storage temperature, shelf life, contamination control and application compatibility must be optimized (Soumare et al., 2020). Importantly, a formulation should preserve functional activity and not merely maintain viable cell counts. Scale-up introduces new constraints. Oxygen transfer, mixing, heat removal, contamination control and substrate costs can change substantially as culture volume increases. Laboratory conditions therefore cannot simply be multiplied to obtain an industrial process. Sensor-based monitoring of pH, temperature, dissolved oxygen and biomass can improve batch reproducibility. Field validation should involve greenhouse experiments followed by multi-location and multi-season trials. Trials should compare inoculated and uninoculated treatments, different mineral-P rates, relevant soil classes and target crops. Measurements should include soil available phosphorus, plant tissue phosphorus, root traits, biomass, yield and phosphorus-use efficiency. (Soumare et al., 2020; Kaur et al., 2024)

8. Integration with Sustainable Nutrient Management

PSM technology is best understood as one component of integrated nutrient management. Soil testing, appropriate mineral fertilizer rates, organic amendments, crop residues, crop rotation and conservation practices can be combined with microbial inoculants. The objective is to synchronize phosphorus release with crop demand rather than treat a single microorganism as a universal replacement for mineral fertilizers. Future formulations may involve microbial consortia containing phosphate-solubilizing organisms together with nitrogen-fixing bacteria, potassium-mobilizing

organisms or mycorrhizal fungi. Compatibility must be demonstrated experimentally because microbial antagonism, instability and ecological interactions can alter performance (Sun et al., 2026). A systems perspective should consider strain × soil × crop × management × climate interactions. (Khan et al., 2007; Cheng et al., 2023; Sun et al., 2026)

9. Emerging Directions

Modern microbial biotechnology provides opportunities to improve strain selection and predict performance. Whole-genome sequencing of promising Arthrobacter strains can identify genes associated with phosphorus metabolism, stress tolerance, transport and secondary metabolism while supporting strain authentication and biosafety assessment. Transcriptomics, proteomics, metabolomics and soil microbiome analysis can further clarify which functions are expressed under agricultural conditions.Precision biofertilization is another promising direction. Inoculant strain, dose and formulation could eventually be matched to soil pH, phosphorus status, crop genotype, moisture and fertilizer history. Digital soil data, remote sensing and decision-support models may help identify conditions under which microbial phosphorus mobilization is most likely to provide measurable benefits. (Kaur et al., 2024; Santoyo et al., 2026; Sun et al., 2026)

For PJC-S08, future studies should examine changes in phosphorus fractions in alkaline soil, expression of phosphorus-mobilization genes, persistence during storage and field application, interactions with native rhizosphere microorganisms, compatibility with reduced mineral-P regimes, use of agro-industrial residues as fermentation substrates, and the life-cycle environmental footprint of production. (Soumare et al., 2020; Kaur et al., 2024; Lei et al., 2025)

10. Conclusion

Microbial phosphorus mobilization represents a scientifically grounded opportunity to improve phosphorus-use efficiency within sustainable agriculture. PSMs can transform poorly available phosphorus through organic-acid secretion, chelation, phosphatase and phytase activity and plant–microbe interactions. Alkaliphilic Actinobacteria are particularly relevant to alkaline soils because environmental adaptation may support activity under high-pH conditions. The supplied research framework surrounding Arthrobacter crystallopoietes PJC-S08 demonstrates an integrated pathway from alkaline environmental isolation to screening, molecular identification, enzyme characterization, process optimization, low-cost medium development, fermentation and plant evaluation. Its sustainability potential depends not only on biological activity but also on formulation stability, production efficiency, biosafety, field consistency and measurable

improvement in nutrient-use efficiency. (Richardson and Simpson, 2011; Alori et al., 2017; Santoyo et al., 2026)

Accordingly, a Microphos-type PJC-S08 bioinoculant should be developed as a complementary technology within integrated nutrient management. Future progress will depend on combining classical microbiology with genomics, formulation science, precision agriculture, field ecology, techno-economic analysis and life-cycle assessment. (Soumare et al., 2020; Kaur et al., 2024; Sun et al., 2026)

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