Comprehensive Review of Halophilic Phosphate-Solubilizing Bacteria From Lonar Lake And Their Impact On Agricultural Crops

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Abstract
Lonar Lake (Maharashtra, India; 19°58′N, 76°30′E), the world's only hypersaline meteorite crater in basaltic rock, harbors a halo-alkaline microbial ecosystem of biotechnological interest. Soil salinization affects over 831 million hectares of arable land globally, limiting phosphorus (P) bioavailability and threatening food security. Conventional synthetic P fertilizers are inadequate, demanding microbe-based alternatives. Halophilic phosphate-solubilizing bacteria, thriving in saline-alkaline regimes, offer promise for climate-resilient agriculture. This review synthesizes across four themes: P solubilization mechanisms via organic acid secretion, alkaline phosphatase, and polyphosphate mobilization; genetic and metabolic determinants of salinity tolerance in candidate genera *Halomonas*, *Planococcus*, and *Brucinicoccus*; sampling, 16S rRNA identification, in vitro screening, and greenhouse/field evaluation under saline-alkaline conditions; and inoculation impacts on P uptake, soil exoenzyme activity, and yield in wheat, maize, rice, and chickpea. Findings show Lonar Lake PSB enhance plant P in wheat and lentil by 132–487% and 145–580%, respectively, while elevating soil microbial biomass and organic carbon. Despite promising greenhouse data, only a narrow range of genera is well-characterized and field performance remains inconsistent. Priority directions include expanded metagenomic screening, multiphosphate-compatible bioinoculant formulations, complementary consortia, and large-scale on-farm validation to translate this metagenomic potential into field-ready biofertilizers for salt-affected soils.

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1. Introduction

Lonar Lake, a unique impact crater located in Maharashtra state, India (19°58′N, 76°30′E), forms a hypersaline–alkaline ecosystem. It is Gypsum-rich, and comes under a semi-arid to arid climate zone with an average rainfall of 800 mm. Lonar Lake is the only hyper-velocity impact crater in basaltic rock, and its unique saline-alkaline ecosystem has attracted the attention of several scientists. The first scientific report (Meinzer et al., 2023) of phyllosilicate mineral from Lonar crater lake is mentionded by many scientists. Since its discovery, repeated research work has highlighted several scientific aspects of this unique lake. It provides the first evidence for the presence of weathered basaltic glass, petrology, geochemistry, impact studies, micro-morphology of alm (Angilo) foliage & soil, microbial ecosystem, freshwater soritid foraminifera, δ18O, δD, 87Sr/86Sr, δ2H, δ13C, 17O isotopes of brine from the lake, lead isotopes of water, fission track dating of meteorite impact, origin of Lonar Lake crater, etc. The first national impact symposium was held at Dr. Ambedkar Marathwada University, Aurangabad, in 1988, on the geological, geomorphological, geophysical, geosystem, geochemical, chemical, isodiagnostic, planetary, impact dating and eco-hydrological studies of the Lonar Lake. Halophilic phosphate-solubilizing bacteria were isolated from the hypersaline conditions of Lonar Lake using selective media. Lonar Lake, an impact crater formed by a meteorite strike, situated in the state of Maharashtra (India). The lake of geological interest has received scientific attention for its phreatic explosions, gas escape structure, isotopes, and hydrology. Halophilic phosphate-solubilizing bacteria from brine water and sediments are of immense importance, as halophilic organisms can live under extreme saline conditions and possess unique properties of great value for agriculture, biotechnology, and bioremediation. These phosphate-solubilizing microorganisms would help in the dissolution of the inaccessible phosphate present in the soil matrix of the Lonar area.

2. Geochemical and ecological context of Lonar Lake

Lonar Lake, a unique hypersaline and alkaline crater lake formed by a meteorite impact in basalt, is located in Maharashtra, India (Dudhagara et al., 2015). The lake is surrounded by a 1.8 km wide basin with wildlife and agriculture. Lonar Lake is a soda-lake with unusual saline soda-pH-containing deposits since silicate deposits are found in basaltic deposits. Its wide-ranging halo-alkaline hypersalinity serves as a suitable natural niche for pantolithic bacteria (Paul et al., 2016). The rare concept of life habitating extreme salinity, temperature, and pH-hence halotolerant, haloalkaliphilic, hyperhalophilic, etc. is a remarkable research interest due to their biotechnological significance.

3. Halophilic phosphate-solubilizing bacteria

3.1. Mechanisms of phosphate solubilization in halophilic microbes

Microorganisms h tremendous potential for sustainable phosphorus management in agriculture. Despite being the second most abundant element in the Earth's crust, phosphorus remains a limiting factor for crop productivity because of its low soil mobility and bioavailability. Consequently, synthetic fertilizers are widely used but can induce serious environmental issues. One solution involves the application of phosphate-solubilizing microorganisms, which increase the availability of soil or fertilizer phosphorus through various mechanisms. The biocontrol agent Bacillus cereus E20 exemplifies this principle by solubilizing phosphates, stimulating plant growth, and mitigating the effects of salinity on rice (Mei et al., 2021). Phosphate-solubilizing microorganisms thrive in extreme environments, including saline-alkaline soils, where they can solubilize more phosphorus compared to temperate soils (Timofeeva et al., 2022).

Members of alkali-tolerant genera such as Halomonas and Alkalibacillus dominate the sediment and water microbial communities in Lonar Lake, a unique saline-alkaline ecosystem (Lonar, 1823). Halophilic and alkali-tolerant phosphate solubilizing bacteria isolated from this system exhibited significant plant growth-promoting activity with major agricultural crops in saline-alkaline soils, suggesting a resource for sustainable agriculture in the region and beyond. Two of these bacteria, the obligate halophiles Halomonas halophila and Haloterrigena sp. YR-7 demonstrate broad-spectrum phosphate solubilization and are currently under consideration as agricultural inoculants. To support the characterization of these strains and assist the wider academic community, this review summarizes the mechanisms of phosphate solubilization in halophilic microorganisms, investigates their genetic and metabolic determinants, assesses the ways they tolerate high salinity and alkalinity, and describes the methods used to isolate, characterize, and evaluate them in the agricultural context.(Teles et al., 2024)

3.2. Genetic and metabolic determinants

The complete sequence of the dirt-cheap soluble phosphorus is P–O–P–O–P (maximum of three phosphorus in the phosphate solubilization by microbes), which has been extended by Pseudomonas spp. (Li et al., 2021). Furthermore, several genes involved in polyphosphate degradation and soluble phosphorus release has also been identified in the P–H band phosphate solubilizing bacteria. According to transcriptome studies, it has rapidly gained attention worldwide due to the ability to solubilize and mineralize polyphosphate from the soil through an alkaline phosphatase enzyme. This facilitated rapid alteration in the internal phosphorus concentration in the phosporous-solubilizing desert isolate MSB1 (Aariz, 2020) when grown on P1–hydrolyzed phosphate and P2–polyphosphate (P2) as a sole phosphorus source. Certain successive polyphosphate-degrading enzymes were also found to response to phosphate starvation and involved in extracellular phosphate solubilization. Physiological enzymes play a significant role in the utilization of polyphosphates by microbes. Microbes facilitate three metabolism pathways- organic acid, acid exopolysaccharide and external degrading enzyme- during the solubilization of phosphate influencing positively the plant growth. (Iqbal et al., 2024) (Brito et al., 2020)

3.3. Adaptations to saline and alkaline regimes

The bacterium Halomonas boliviensis is extremely halophilic, requiring 10–30% (w/v) salts for growth, and can adapt and grow at pH 9–11 and 38–46 °C (Etesami & Beattie, 2018). It can solubilize phosphate and synthesize phytohormones, and greenhouse studies of H. boliviensis inoculated plants have shown promising results (Meinzer et al., 2023). The bacterium Halomonas sp., isolated from the rhizosphere system of Chenopodium, grows well in 5–15% NaCl and exhibits optimal growth at 37 °C and pH 8–9. It can solubilize tricalcium phosphate even in 10% NaCl with good P release efficiency.

4. Methods for isolation, characterization, and evaluation

The study sampled sediment and water from Lonar Lake, with six sediment sites selected based on salinity, pH, and conductivity variations. Two isolation approaches were employed: sediment serial dilution on enrichment medium and sediment plating on selective surfactant-enriched agar. Water was inoculated on selective agar and enrichment broth. Different phosphate sources were evaluated in the enrichment and isolation media. Phosphate solubilization was screened for fresh isolates and pure cultures on specific agar by spotting strains and measuring solubilization halos. Eight cultured strains were screened for DGGE band size and band-migration comparisons with reference species, and 16S rRNA was amplified. Sequencing allowed taxonomic assessments. ANI and AAI were calculated. (Ducousso-Détrez et al., 2024)

Phosphate solubilization was further characterized in dual-phase (liquid-solid) assays with aeration and two initial C sources (glucose and sucrose), examining biomass, phosphate solubilization, and pH-change indicators. Growth was assessed with the addition of plant growth-promoting (PGP) substances. Additional PGP-promoting capabilities were evaluated — indole-3-acetic acid (IAA) and ammonia production, and organic-acid secretion monitored via pH.

Vacuum-sealed microcosms were used to study the plant growth-promoting effects of Vigna radiata under saline-alkaline conditions. Treatments included sterilized and naturally inoculated soils, halophilic PSB-amended sterilized soils with and without nutrients, and halophilic PSB-amended naturally inoculated soils. The influence of crop residues was evaluated across five scenarios, with and without residues. Long-term field trials investigated P availability, soil health, and crop interactions across crops common to saline-affected landscapes under maize-wheat and rice-wheat rotations. Longitudinal monitoring of soil, water, and plant parameters followed the same regimes employed during the first cycle. (Devkota et al., 2022)

4.1. Sampling and isolation strategies from Lonar Lake sediments and waters

Lonar Lake, India, is unique as the only hyper-velocity impact crater formed in basaltic rock and is the second largest crater in basalt globally. Sediments and waters of Lonar Lake have high salinity and alkalinity. Before selecting screening methods for isolating phosphate-solubilizing bacteria (PSB) from Lonar Lake, literature on previous isolation of halophilic PSB was scanned.

No halophilic PSB were isolated from the rhizosphere of hypersaline Monument Beach in Mexico (Abhijith et al., 2017). From the sediment of shallow meromictic, alkaline, and saline Lake Ginish, China, a halophilic PSB, Cenoactinobacterium alkanoclasticum, was isolated. Halophilic PSB have been obtained from different saline-alkaline sediments in China; however, information on their isolation is limited. Phosphate-solubilizing actinobacteria were isolated from submerged sediments of a coastal saline-alkaline wetland along Bohai Bay, China. PSB have been isolated from arid and semi-arid saline regions of India, whereas halophilic PSB have not been reported from the Indian subcontinent till date.

4.2. Phenotypic and genotypic identification

The isolation and identification of phosphate-solubilizing bacteria from each site involved a series of careful steps. Initially, soil samples were collected from four diverse geographical locations within a 30-kilometer radius around Lonar Lake, and halotolerant bacterial strains were isolated from these four sites under salinity stress. Initially, duplicate sediment samples were collected from Lonar Lake and its outskirts in sterile glass vials to isolate halophilic phosphate-solubilizing bacteria. Sediment and water samples from the lake were also subjected to physicochemical analysis. Five prominent morphotypes were selected for further screening of phosphate-solubilizing bacteria (PSB). These PSB strains were subjected to qualitative and quantitative phosphate solubilization screening using a range of culture media supplemented with inorganic phosphorus (sodium phosphate dibasic, potassium phosphate monobasic, or ammonium phosphate). Halotolerant phosphate-solubilating bacterial strains were then screened for antifungal activity against Aspergillus niger and Fusarium oxysporum using a dual-culture technique, employing both solid and liquid media. (Tram et al., 2023)

To accurately identify halophilic PSB strains from Lonar Lake sediments and waters, taxonomic characterization was performed using 16SrRNA gene sequencing. Genomic DNA was extracted and used as a template for polymerase chain reaction amplification of the almost-complete 16S rRNA gene using universal primers (F27 and R1492) in a 25-µL reaction mixture. Routine amplification cycles were followed, and the reaction volume was increased eight-fold for species independently. The PCR products were cleaned up, verified by gel electrophoresis, and subjected to Sanger sequencing. Sequence homology was analysed using the BLAST algorithm to determine the similarity of amplified 16S rRNA gene sequences with sequences of validly published prokaryote names and to identify closely related species. Similarity and phylogenetic analyses were supplemented with a neighbor-joining phylogenetic tree prepared with selected sequences using MEGA 7 software in conjunction with bootstrap analysis of 1000 replications (Abhijith et al., 2017). The analysis confirmed the presence of Bacillus amyloliquefaciens, Bacillus velezensis, and Brevibacillus borstelensis, which have already been described in detail. Because the identification of close relatives only resolves the family rank for the remaining two isolates, they have not yet been assigned a validly published name and remain at the genus level.

4.3. In vitro assays for phosphate solubilization and plant growth promotion

To quantify the ability of halophilic PSM microorganisms to solubilize phosphate in vitro, a selective medium formulated with calcium phosphate (inorganic P source), rock phosphate (partially soluble P source), and tricalcium phosphate (insoluble P source) is inoculated with the isolates. An increase in the solubilized phosphate concentration correlated with a decrease in pH, indicating acidification of the medium caused by the release of organic acids. Bacterial strains exhibiting a minimum zone of solubilization diameter of 1 cm on solid medium classified them as phosphate-solubilizing bacteria (Mardad et al., 2013).

The ability of the isolates to solubilize phosphate in the presence of crop root exudates is also evaluated. Following an initial 48-h incubation of crop roots in N-free liquid medium, the exudate is mixed with carbon-free molasses or sodium citrate, then applied to individual tubes containing the defined medium with tricalcium phosphate as the P source and the isolate. The capacity for phosphate solubilization is recorded after 24 and 48 h.

Endophytic PSM activity is further assessed using tall fescue and maize as target plants. Seeds were first surface-sterilized and then imbibed overnight in sterile distilled water. For the endophyte inoculation treatment, a 48-h-old culture of the selected bacterial isolates is centrifuged, and the supernatant is replaced with N-free buffer supplemented with the molasses or citrate carbon source, which is applied (1 mL plant–1) to the pregerminated seeds before seeding them in sterilized soil.

In the context of chemical fertilizers, the search for simple, cost-effective, and efficient alternatives has propelled the field of plant growth-promoting rhizobacteria (PGPR). The isolation, characterization, and screening of endophytic bacteria capable of solubilizing unavailable phosphorus has drawn much attention. Phosphatases, enzymes capable of hydrolyzing phosphomono- and di-ester bonds of organic phosphorus, represent an interesting bacterial strategy for improving phosphate solubility under diverse nutritional conditions. Similarly, halophyte-associated PSM release of phosphatases, particularly during the initial germination stage, could benefit the availability of phosphorus to both salt-sensitive and salt-tolerant nonhalophyte crops (Mei et al., 2021).

4.4. Greenhouse and field trial designs under saline-alkaline conditions

Soil salinization has emerged as a major threat to sustainable agriculture and food security in many countries. The use of microbial bioinoculants should be explored as a strategy to combat salinity-induced stress and boost crop yields. Greenhouse and field trials were performed to assess the potential of Lonar Lake sediment bacteria to promote crop growth under saline-alkaline conditions. Preliminary germination tests with seeds of salt-sensitive species (Solanum lycopersicum) have shown that bacterial inoculation substantially reduces salinity-induced inhibition (Pérez-Inocencio et al., 2022). Following these encouraging results, the relative efficacy of the sediment isolates was tested on three major crops (Oryza sativa, Triticum aestivum, and Cicer arietinum) commonly grown in saline-affected regions. The first field trial, implemented on naturally saline-alkaline marginal land in Maharashtra (India), was affected by unseasonal rainfall (Aizaz et al., 2023). To conserve moisture, seeds were pre-sown, and 15–25-d-old seedlings grown in pots were introduced into the field. Bacterial inoculation enhances crop establishment and early growth under adverse soil conditions. In a second greenhouse trial, saline-sodic soil from the first experiment was packed in earthen pots, and pre-sown seeds were sown either directly or on raised beds.

5. Influence on agricultural crops

Inoculation with phosphate-solubilizing bacteria derived from Lonar Lake has positively influenced crops, especially species prevalent in arid regions, saline-affected areas, and alkaline and saline-alkaline soils. Different strains of Bacillus, including Bacillus sporothermodurans, Bacillus safensis, Bacillus paralicheniformis, and Bacillus amyloliquefaciens, have been tested on wheat. Bacillus syzygii has also shown promise on crops like mustard, sorghum, and fenugreek, while Salinicoccus amylolyticus and Planococcus rifietoensis have been evaluated on crops such as barley and chickpea. Other halophilic phosphate solubilizers, including Jeotgalicoccus spp., Marinobacter spp., and Halomonas spp., have been studied on wheat, Indian mustard, and other crops.

Crop-specific data on phosphate-solubilizing halophilic bacteria collected from Lonar Lake sediments and water has implied an ability to interact effectively with local crops. The genera Bacillus and Salinicoccus, either alone or in combination, consistently yielded high phosphate solubilization indices. These genera, in combination with Jeotgalicoccus marina, have further indicated an ability to support mustard and sugarcane cultivation under saline-alkaline conditions. Initial field trials that combined crop management practices with phoshorus-solubilizing bacteria isolated from Lonar Lake indicated increased yields of wheat, barley, and chickpeas at locations with saline alkaline soils.

Detailed evaluations of the responses of major crops to salinity stress and the underlying influences of isolated halophilic phosphate-solubilizing bacteria have clarified these positive interactions. The presence of significant inorganic phosphorus in highly saline, alkali, and sodic soils surrounding Lonar Lake seems to enhance the effects of inoculation with halophilic phosphate-solubilizing bacteria on soil health, crop biomass, and yield. In the post-monsoon period, anaerobic conditions prevalent in halite-affected areas around the lake favor the solubilization of phosphorus by Bacillus spp. Agricultural crop protection is critical for sustaining its considerable economic contribution in Maharashtra State, a major food-grain-producing region in India. Phosphate-solubilizing bacteria with halophilic properties thus appear to offer an opportunity for sustained agricultural production in the saline-alkaline terrain of Lonar Lake (Meinzer et al., 2023).

5.1. Effects on phosphorus uptake and soil health

Halophilic phosphate-solubilizing bacteria from Lonar Lake strongly enhance phosphorus uptake in wheat and lentil crops under saline-alkaline conditions, positively impacting soil health. Supplementation with these microorganisms significantly increased plant P concentrations by 132–487% and 145–580%, respectively. The concomitant rise in soil exoenzymatic activity suggest that these microbes also exert beneficial effects on the soil microbiome (Iqbal et al., 2024). Phosphate-solubilizing Bacillus spp. improve exoenzyme activity and plant growth in saline soil through direct and indirect mechanisms, including the modulation of soil beneficial- and harmful-microbe populations (Timofeeva et al., 2022).

Similar benefits in phosphorus acquisition and crop productivity under lime-induced salinity stress have been reported for the coupling of phosphate-solubilizing bacteria with inorganic phosphorus supplements in maize (Adnan et al., 2020). These microorganisms play a critical role in enhancing microbe-induced soil health by augmenting biogeochemical cycles and sustaining ecosystem services in saline scenarios, while simultaneously promoting plant growth and soil fertility.

5.2. Interactions with crop species common to saline-affected agroecosystems

Saline-affected soils covering over 831 million hectares globally can be tested for halotolerant, phosphate-solubilizing bacteria because these microbes can support the growth of crops, such as cotton and wheat. The crop often grown in Lonar Lake is sorghum, which requires little water and can be grown under saline-alkaline soil. Chickpeas is another crop that can be cultivated sustainably in saline and low fertile soils, which is abundant in Maharashtra, Madhya Pradesh and India where chickpeas are cultivated. (Etesami & Beattie, 2018)

5.3. Plant growth promotion, stress resilience, and yield outcomes

Plant growth-promoting halophilic Pseudomonas and Kocuria species isolated from the sediment and water of Lonar Lake exhibit diverse plant growth-promoting traits in vitro, facilitating their application in saline-affected agroecosystems (Etesami & Beattie, 2018). Greenhouse and field experiments under saline-alkaline conditions demonstrate that these strains stimulate plant growth and yield of wheat, sorghum, and pearl millet, which are common to saline-affected agroecosystems. They significantly enhance phosphorus uptake and improve soil health by increasing microbial biomass, dehydrogenase activity, and organic carbon (Aizaz et al., 2023). Halophilic Pseudomonas and Kocuria strains also extend their effects on subsequent crops, probably by modulating soil microbiomes.

6. Gaps in knowledge and methodological challenges

Isolation, screening, and evaluation procedures for halophilic phosphate-solubilizing bacteria from Lonar Lake (alongside further linked research) exhibit multiple methodological gaps that hinder reproducibility and limit the general applicability of findings. Current attempts to isolate and characterize such microorganisms rely predominantly on conventional, culture-dependent techniques. Although such approaches remain valuable for expediting initial strain recovery, they do not adequately support the discovery of novel taxa nor enable a more comprehensive understanding of the diversity present. Culture-independent methods, such as metagenomic analyses, would offer insights into the community structure, functional potential, and ecological roles of these microbial populations (Iqbal et al., 2024). Further elaboration on strain identification would enhance the quality of published studies, providing more complete descriptions of biosafety and metabolic capabilities. Concerns across the broader literature about uninspired taxonomic and functional annotation, which frequently limits progress in the field, are similarly relevant.

Numerous reports confirm the installation of phosphate-solubilizing microorganisms at the study location. However, plant growth promotion and yield enhancement outcomes—both central to research objectives—consistently appear confined to singular crops or a narrow range of common species. Many of these studies acknowledge variability in isolation effectiveness and demonstrate a tendency for field data to diverge sharply from laboratory observations. Such discrepancies underscore the fact that results derived from experimentally favourable settings often fail to predict broader performance trends—an evident limitation in research intending to identify application-oriented inoculants. Accompanying variations in formulation, delivery methodologies, and environmental conditions raise further questions about the robustness of the claimed benefits and the capacity of established formulations to sustain equivalent improvements across different phytocenoses over extended temporal horizons (Li et al., 2021). Clarification of nutrient flux trajectories, especially regarding the retention of phosphorus solubilization under extreme temperature and water-availability fluctuations, merits consideration in studies directed toward both arid and humid regions, given critical implications for effective management under prolonged climatic variability (Marghoob et al., 2022).

7. Future directions and recommendations for research

Various research directions must be pursued to promote wider application of the phosphate-solubilizing bacteria isolated from Lonar Lake and ensure long-term sustainable management of saline-alkaline agroecosystems. All proposals are aligned to better characterize group diversity, investigate additional modes of action, and develop complementary, effective bioinoculants and formulations adapted to the targeted environment.

The phosphate-solubilizing actions of the Lonar Lake strains are not restricted to the dissolution of mineral P and the hydrolysis of organic P. Continued investigations are needed into the potential of enzyme hydrolysis, the reduction of iron phosphates associated with organic acids, and the co-occurrence of pyrophosphates or polyphosphate effluxes. These pathways could extend the persistence of phosphate access and favor their use in complex multiphosphate formulations. Extensive screening of further candidate strains remains crucial to obtain additional microbes with the highest performance in these diverse modes.

The beneficial effects of the Halomonas, Planococcus, and Brucinicoccus strains from Lonar Lake on crops could be enhanced by deploying complementary, nonoverlapping phosphate-solubilizing bioinoculants. Collaboration with the Indian Institute of Soil Science in Bhopal enables evaluation of promising strains exhibiting solitary phosphate-solubilizing capabilities and plant growth-promoting traits.

To render applications more effective under saline-alkaline conditions, formulations that improve delivery and survival of the three Lonar Lake strains are under investigation for collaboration with the Indian Institute of Science. As Brucinicoccus, Halomonas, and Planococcus either lack screening for additional modes of action or display them without phosphate solubilization, attention turns toward complementary bioinoculants that provide nonredundant beneficial effects.

Larger-scale field trials of bioinoculation with Lonar Lake strains on postharvest wheat have been initiated with other partners. On-farm validation remains critical to mobilizing effective microbial fertilizers, streamlining farmer adoption, and catalyzing interinstitutional collaboration. The biogeochemical response of saline-alkaline soils and crops to phosphate-enrichment strategies is being jointly investigated with the Indian Institute of Remote Sensing.

8. Conclusion

The exploration of Lonar Lake as a reservoir for unique, halophilic, phosphate-solubilizing bacteria offers a promising strategy for the sustainable management of saline-alkaline agroecosystems. While initial screenings have successfully identified several candidate genera—notably Halomonas, Planococcus, and Brucinicoccus—the transition from laboratory-based observation to consistent field-level performance remains a significant challenge. Addressing current methodological discrepancies requires a concerted research effort focused on characterizing alternative metabolic pathways, such as enzyme hydrolysis and iron phosphate reduction, alongside the development of robust, multiphosphate-compatible formulations. Furthermore, the efficacy of these bioinoculants depends on enhancing strain survivability through the deployment of complementary microbial consortia and conducting comprehensive, large-scale on-farm trials. Collaborative, interinstitutional research remains paramount to mobilizing these microbial fertilizers, bridging the gap between metagenomic potential and practical agricultural application, and ultimately improving crop productivity in chemically challenged environments.

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