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LIVING PHOSPHOROUS BIOFERTILIZERS: INTEGRATING BIOCHAR–MICROBIAL ENGINEERING, AGRICULTURAL EXTENSION AND FARMER ADOPTION FOR SUSTAINABLE PHOSPHORUS MANAGEMENT

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ABSTRACT

Phosphorus deficiency remains a major constraint to crop production, while dependence on mineral phosphorus fertilizers is increasingly challenged by low nutrient-recovery efficiency, price volatility, geographically concentrated phosphate resources and environmental losses. This review develops the concept of living phosphorus biofertilizers as an integrated nutrient-management platform that combines functional biochar, phosphorus-mobilizing microorganisms and plant–soil interactions. A structured literature search covered major scientific databases and authoritative institutional sources from 2010-2025, with earlier seminal studies included where necessary. Evidence indicates that biochar can retain phosphorus, modify soil chemical conditions and provide protected microsites for microbial colonization, whereas phosphate-solubilizing bacteria, fungi and mycorrhizal associations can mobilize mineral and organic phosphorus pools. Selected laboratory, greenhouse and field studies support the potential of combined biochar–microbial systems, but the fully integrated living phosphorus biofertilizer remains a proposed framework that requires multi-location and multi-season validation. The review therefore extends beyond technical performance to examine commercialization, product quality, farmer risk perceptions, extension communication, participatory trials, digital decision support, gender and social inclusion, and public–private delivery models. A science-to-farm framework is proposed in which formulation, regulation, demonstration, advisory support and farmer feedback operate as a continuous learning cycle. Living phosphorus biofertilizers could complement rather than immediately replace mineral fertilizers, provided that field efficacy, product consistency, economic feasibility and locally adapted extension recommendations are established.

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INTRODUCTION

Phosphorus is an essential macronutrient involved in energy transfer, photosynthesis, nucleic-acid synthesis, membrane function, root development and reproductive growth. Modern crop production therefore depends heavily on phosphorus inputs, particularly in soils where the concentration of plant-available orthophosphate is low. Yet phosphorus is one of the least efficiently recovered fertilizer nutrients. In many soils, a large share of applied phosphorus is rapidly adsorbed or precipitated with calcium, iron or aluminum compounds, and crop recovery during the season of application is often only

10–30% (Hinsinger, 2001; Withers et al., 2018; Alotaibi et al., 2021; Bai et al., 2024).

Low recovery efficiency has agronomic, economic and environmental consequences. Repeated fertilizer application raises production costs and can enlarge legacy phosphorus pools in soil. Phosphorus transported through runoff and erosion also contributes to eutrophication and degradation of freshwater ecosystems (Carpenter, 2008; Schindler et al., 2016). At the same time, phosphate rock is a finite geological resource whose production and trade are geographically concentrated, exposing fertilizer-dependent farming systems to market and supply-chain risk (Cordell et al., 2009; Cordell and White, 2014; IFA, 2024). These pressures are particularly important for smallholder and resource-constrained farmers who have limited capacity to absorb sudden increases in input prices.

Sustainable phosphorus management therefore requires more than substituting one fertilizer product for another. It requires strategies that improve access to existing soil phosphorus, recover phosphorus from renewable or recycled materials, synchronize nutrient release with crop demand, and reduce avoidable losses. Biochar and phosphorus-mobilizing microorganisms are promising components of such strategies. Biochar can alter soil pH, retain nutrients, provide reactive surfaces and create porous microbial habitats, although its effects depend strongly on feedstock, production conditions, soil properties and application rate (Glaser and Lehr, 2019; Joseph et al., 2021). Phosphate-solubilizing bacteria and fungi mobilize poorly available phosphorus through organic-acid production, proton release, chelation and phosphatase or phytase activity, while mycorrhizal fungi extend the effective soil volume explored by roots (Sharma et al., 2013; Alori et al., 2017).

Evidence for combined biochar–microbial systems is emerging. Biochar-supported phosphorus-solubilizing bacteria have improved microbial persistence, soil phosphorus availability and plant growth in controlled studies, and field-scale work with functionalized biochars has shown that phosphorus retention and microbial mineralization can operate together (de Amaral Leite et al., 2020; Ibrahim et al., 2024; Bai et al., 2024). Nevertheless, technical promise does not automatically produce farmer adoption. Product inconsistency, limited field validation, inadequate extension support, uncertain profitability and unequal access to information can prevent useful technologies from moving beyond experimental settings.

This review uses the term living phosphorus biofertilizer to describe a proposed biologically active platform that integrates functional biochar, a compatible consortium of phosphorus-mobilizing microorganisms and an appropriate phosphorus source or soil phosphorus pool. The concept is deliberately broader than a conventional microbial inoculant. It emphasizes the coordinated retention, mobilization and rhizosphere delivery of phosphorus, together with the extension and institutional arrangements required for practical use. The objectives are to: examine the limitations of conventional phosphorus fertilization; synthesize evidence on biochar and microbial phosphorus mobilization; define the living phosphorus biofertilizer framework and its scientific boundaries; assess agronomic, environmental and economic implications; and identify extension, advisory and adoption pathways for responsible scaling.

Review Methodology

The review followed a structured narrative-review process informed by the principles of transparent systematic searching and screening. Literature was identified in Web of Science, Scopus, ScienceDirect, SpringerLink, CAB Abstracts, AGRICOLA, PubMed and Google Scholar. Authoritative reports from the Food and Agriculture Organization of the United Nations, the International Fertilizer Association, the World Bank and related international organizations were included when they provided policy, market or extension-system context not available in journal articles. The main search period was January 2010-2025. Earlier seminal publications were retained when they established foundational concepts in phosphorus chemistry, microbial solubilization, diffusion of innovations or agricultural extension.

Search strings combined terms related to phosphorus management, diammonium phosphate, phosphate-solubilizing bacteria, phosphate-solubilizing fungi, mycorrhizae, biochar, phosphorus-enriched biochar, microbial carriers, biofertilizers, phosphorus-use efficiency, farmer adoption, agricultural extension, advisory services, participatory trials, digital agriculture and decision support. Boolean operators and alternative spellings were used to increase recall. Searches were supplemented by backward and forward citation tracking of highly relevant publications.

Studies were eligible when they addressed at least one of four domains: phosphorus constraints and recovery efficiency; biochar-mediated phosphorus retention or availability; microbial phosphorus mobilization and biofertilizer performance; or extension, adoption and commercialization of biological agricultural inputs. Peer-reviewed research articles, review papers, meta-analyses and authoritative institutional reports were considered. Duplicate records, conference abstracts, papers without sufficient methodological information, non-English items that could not be reliably assessed, and studies with no direct relevance to the review questions were excluded.

The search produced 936 records. After 168 duplicates were removed, 768 titles and abstracts were screened. Of these, 234 full texts were assessed, 76 were excluded at the eligibility stage and 158 studies were included in the qualitative synthesis. Information was extracted on biochar feedstock and production conditions, microbial taxa and functions, soil and crop context, experimental scale, phosphorus outcomes, formulation characteristics, adoption factors and extension mechanisms. Findings were synthesized thematically rather than statistically because the included literature used heterogeneous materials, treatments, measurements and study designs.

The review has two limitations. First, the proposed living phosphorus biofertilizer is an integrative concept, and direct evidence for the complete platform is still limited; most conclusions therefore arise from studies of individual components or selected combinations. Second, the literature is dominated by laboratory, incubation and greenhouse studies, with fewer multi-season field trials and relatively little farmer-level economic or adoption evidence. These limitations are treated as research priorities rather than concealed through extrapolation.

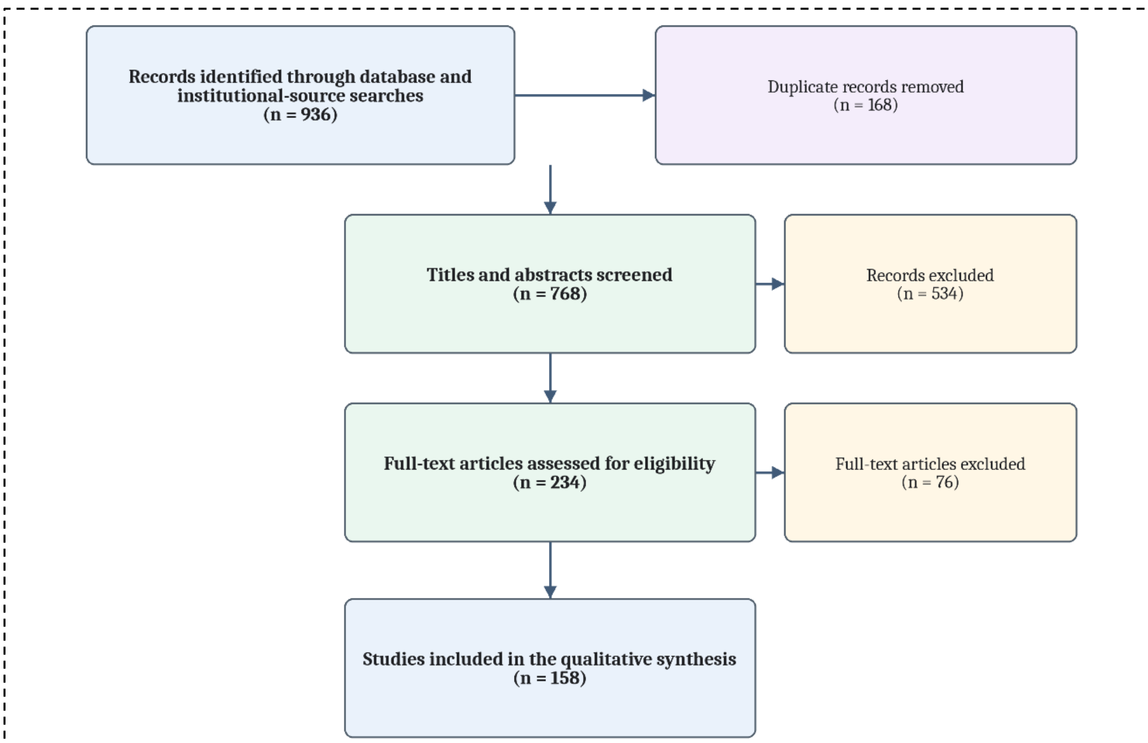

Figure 1. Structured review process informed by PRISMA principles.

Phosphorus Security and the Limits of Conventional Fertilization

Phosphorus security has two related dimensions: access to phosphate resources and effective use of phosphorus already present in agricultural systems. Phosphate rock is non-renewable on human time scales, and economically important reserves and processing capacity are concentrated in a limited number of countries. Import-dependent agricultural economies are therefore vulnerable to geopolitical disruption, energy costs, transport constraints and fertilizer-price volatility (Cordell and White, 2014; IFA, 2024). The problem is not that phosphorus will suddenly disappear, but that affordable and equitable access can become increasingly uncertain.

The second dimension is poor nutrient recovery. In acidic soils, soluble phosphorus readily associates with iron and aluminum oxides; in calcareous soils, it can precipitate with calcium. Organic phosphorus may also remain unavailable until mineralized. As a result, farmers often apply fertilizer to overcome chemical fixation rather than to replace only the phosphorus removed in harvested products. This practice can sustain yield, but it also increases costs and contributes to the accumulation of residual or legacy phosphorus (Hinsinger, 2001; MacDonald et al., 2011; Withers et al., 2018).

Legacy phosphorus is both a liability and a potential resource. When mobilized too rapidly or transported by erosion, it can increase water-quality risks. When mobilized in synchrony with crop demand, it can reduce the need for new mineral inputs. Sustainable management therefore requires soil-specific approaches that balance crop nutrition, legacy-pool activation and loss prevention. Biological mobilization is particularly attractive because it can operate in the rhizosphere, where plant demand, microbial activity and soil chemistry interact.

The role of mineral fertilizer should consequently be reframed. Biological products are unlikely to eliminate mineral phosphorus immediately across all soils and crops. A more credible objective is integrated phosphorus management: reduced or better-timed mineral inputs, improved recovery, greater use of recycled phosphorus, and biological activation of soil pools. This position avoids presenting living phosphorus biofertilizers as a universal substitute before field evidence is available.

Biochar as a Phosphorus-Engineering Material

Biochar is produced by thermochemical conversion of biomass under oxygen-limited conditions. Its agricultural behavior is not uniform. Feedstock type, pyrolysis temperature, residence time, ash content, particle size, surface oxidation and post-production treatment influence pH, porosity, mineral composition, functional groups and contaminant risk. Consequently, the term biochar describes a family of materials rather than a single standardized input (Joseph et al., 2021).

Biochar can influence phosphorus in several ways. Phosphorus-rich feedstocks can yield chars that act as nutrient sources, whereas mineral-modified chars can adsorb phosphorus and support gradual release. Biochar can also alter soil pH and ionic conditions, potentially reducing phosphorus sorption in acidic soils. Meta-analytic evidence indicates that biochar often increases plant-available phosphorus, but responses vary by soil pH, feedstock, application rate and production temperature, and some alkaline or highly sorptive systems show little benefit (Glaser and Lehr, 2019). The effects should therefore be predicted and tested rather than assumed.

The porous structure of biochar is especially relevant to microbial delivery. Pores and surfaces can protect inoculated microorganisms from desiccation, predation and rapid washout, while retained water and nutrients can support colonization. Biochar can also alter indigenous microbial communities and enzyme activity. These effects are context-dependent, and a carrier that is suitable for one microbial strain may be unsuitable for another because of pH, salinity, volatile compounds or pore-size distribution (Palansooriya et al., 2019; Joseph et al., 2021).

Biochar engineering therefore requires explicit quality criteria. Feedstock traceability, controlled production, contaminant testing, pH and electrical conductivity, nutrient content, particle-size distribution, water-holding capacity and microbial compatibility should be documented. For phosphorus applications, retention and release behavior must also be tested under relevant soil conditions. Without these controls, variable products may reduce farmer confidence and undermine extension recommendations.

Microbial Engineering of Phosphorus Availability

Agricultural soils contain diverse microorganisms that transform inorganic and organic phosphorus. Phosphate-solubilizing bacteria, including species of Bacillus, Pseudomonas, Rhizobium, Enterobacter and related genera, can release organic acids and protons that dissolve calcium phosphates or alter mineral equilibria. Phosphate-solubilizing fungi, including Aspergillus and Penicillium, can produce substantial quantities of organic acids and enzymes. Other organisms mineralize organic phosphorus through phosphatases and phytases, while mycorrhizal fungi acquire phosphorus through extensive hyphal networks beyond the immediate root-depletion zone (Sharma et al., 2013; Alori et al., 2017).

Microbial functions are not interchangeable. A strain that performs strongly in culture medium may fail in soil because of competition, predation, unsuitable pH, limited carbon, temperature stress or poor root colonization. Functional screening should therefore move beyond a single solubilization halo. Relevant traits include persistence, compatibility with the target crop and soil, enzyme activity, organic-acid profile, tolerance to formulation and storage, and the absence of pathogenic or antimicrobial-resistance risks. Consortia may provide complementary functions, but greater diversity does not automatically improve performance. Strains can compete or inhibit one another, and mixed formulations can be difficult to stabilize. Rational consortia should be assembled around defined functions and tested for compatibility. The plant microbiome literature also emphasizes that host genotype, growth stage, soil history and environmental conditions shape microbial establishment and function (Compant et al., 2019; Berg et al., 2020).

Carrier selection is therefore central to microbial engineering. A suitable carrier protects cells during storage and application, enables an adequate viable population at the point of use, and supports establishment in the rhizosphere. Biochar is promising because it can combine microbial support with phosphorus retention, but its suitability must be demonstrated for each formulation rather than inferred from porosity alone.

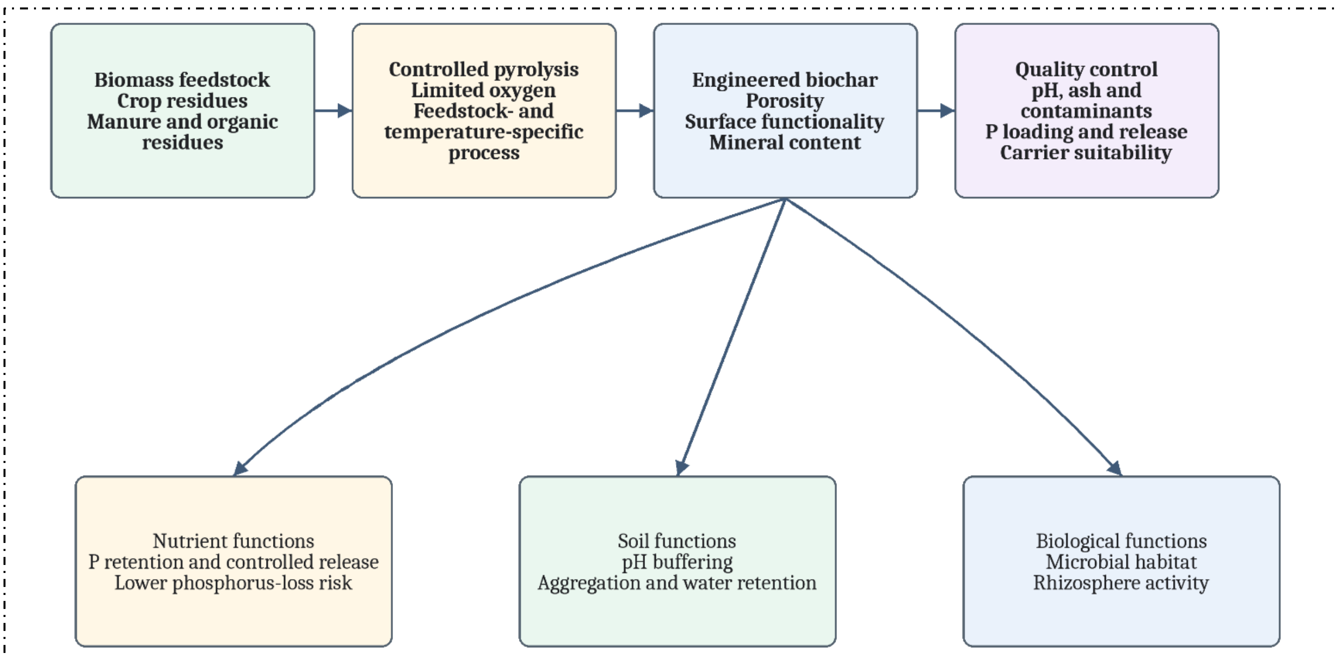

Figure 2. Biochar as a phosphorus engineering material.

Synergy Between Biochar and Phosphorus-Mobilizing Microorganisms

The scientific rationale for combining biochar with phosphorus-mobilizing microorganisms is based on complementary functions. Biochar can retain water and nutrients, alter the chemical environment and provide protected attachment sites. Microorganisms can release organic acids and enzymes that mobilize phosphorus from minerals, organic matter or nutrient-loaded char. If these processes are coordinated, the carrier can reduce immediate phosphorus loss while microbial activity maintains a biologically regulated supply.

Experimental evidence supports this possibility, although the strength of evidence varies. In a pot study, bacterial strains applied with a biochar-based rock-phosphate fertilizer increased soil phosphorus availability and maize growth (de Amaral Leite et al., 2020). Biochar-immobilized Pseudomonas sp. improved rhizosphere colonization, phosphorus availability and tomato growth under phosphorus stress (Bai et al., 2024). Field research with magnesium-functionalized biochars showed that phosphorus retention, slow release and microbial genes associated with solubilization and mineralization can contribute simultaneously to greater phosphorus availability and maize performance (Ibrahim et al., 2024). More recent controlled work has also reported stronger responses from integrated biochar–microbial treatments than from individual amendments, although full factorial designs and long-term field confirmation remain necessary (Song et al., 2025). These findings support a complementary interaction but do not justify assuming universal synergy. Biochar may adsorb microbial metabolites, immobilize phosphorus too strongly, raise pH beyond the optimum for a strain, or introduce salinity and contaminants. Indigenous microorganisms may displace the inoculant, and field moisture or temperature may reduce viability. The combined system must therefore be optimized around the target soil, crop and application method.

A rigorous development pathway should compare the complete formulation with its individual components, conventional fertilizer, reduced-fertilizer combinations and an untreated control. Microbial survival, phosphorus fractions, plant uptake, yield, environmental losses and economic outcomes should be measured over more than one season. Such designs can distinguish genuine interaction from simple nutrient addition.

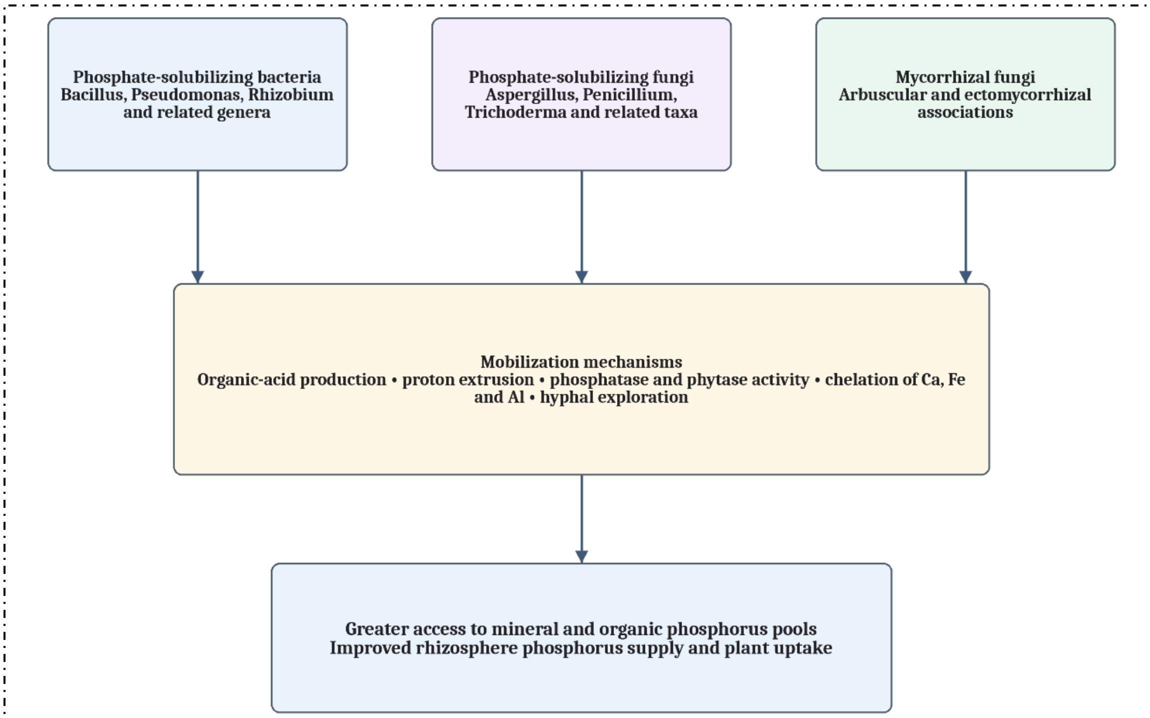

Figure 3. Major phosphorus-mobilising microorganisms and mobilisation mechanism.

Living Phosphorus Biofertilizer: Concept and Boundaries

A living phosphorus biofertilizer is proposed here as a formulated system containing three coordinated elements: a functional biochar carrier; a compatible microbial consortium with demonstrated phosphorus-mobilizing activity; and a phosphorus source or soil phosphorus pool that can be retained, transformed and delivered in the rhizosphere. The phosphorus component may include legacy soil phosphorus, recycled phosphorus, low-solubility mineral sources or a reduced dose of conventional fertilizer. The defining feature is not complete freedom from mineral fertilizer, but biologically regulated phosphorus delivery.

The framework differs from conventional biofertilizers in four respects. First, the carrier is designed as an active phosphorus-management material rather than an inert support. Second, microbial functions are selected to complement the chemical properties of the carrier and target soil. Third, phosphorus retention and release are evaluated together rather than separately. Fourth, extension, quality assurance and farmer feedback are treated as components of the innovation system, not activities added after product development.

The term living should not imply that the product is self-sustaining indefinitely. Microbial populations may decline, community composition may change and repeated application may be necessary. Product labels should specify viable count, storage conditions, shelf life, application method and the soils or crops for which evidence exists. Claims should be limited to outcomes demonstrated under appropriate trials.

The present evidence base is strongest for individual components and selected pairwise combinations. The complete platform remains conceptual. This distinction is important for scientific credibility and for regulatory classification. A product that combines fertilizer, soil amendment, microbial inoculant and recycled nutrient source may fall across several regulatory categories. Clear definitions and performance standards will be needed before commercialization.

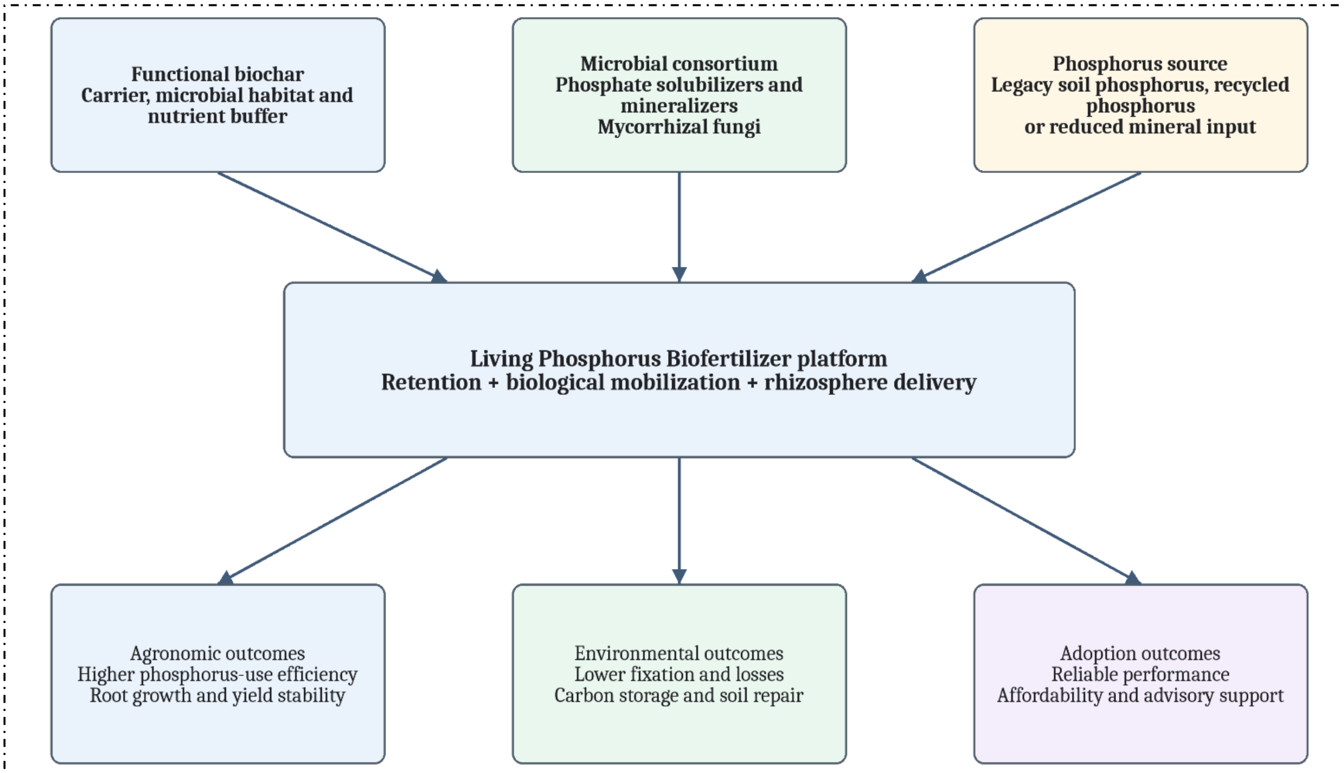

Figure 4. Proposed living phosphorus biofertilizer framework and intended outcomes.

Table 1. Evidence base and development readiness of major living phosphorus biofertilizer components.

Component	Current evidence	Main uncertainty	Priority before scaling
Functional biochar	Substantial laboratory, greenhouse and some field evidence for changes in soil properties and phosphorus availability.	Highly variable response among feedstocks, soils and production conditions.	Standardized characterization, contaminant testing and soil-specific performance criteria.
Phosphorus-mobilizing microorganisms	Strong mechanistic evidence and many crop studies; commercial inoculants already exist.	Inconsistent survival, colonization and field performance.	Strain identity, viable count, shelf life, biosafety and multi-season efficacy.
Biochar–microbial combinations	Growing evidence that biochar can improve inoculant persistence and phosphorus outcomes.	Limited factorial and long-term field studies; mechanisms may be context-specific.	Component controls, microbial tracking, phosphorus-fraction analysis and multi-location trials.
Integrated living phosphorus biofertilizer	A coherent conceptual platform supported indirectly by component studies.	No broadly standardized product or validated universal formulation.	Prototype development, regulation, economics, participatory testing and extension protocols.

Agronomic, Environmental and Economic Implications

Agronomic implications

Agronomically, the main value proposition is improved phosphorus-use efficiency rather than simply higher phosphorus concentration in soil. A useful product should increase plant uptake, root development or yield at the same phosphorus input, or maintain performance with a lower mineral-fertilizer dose (Weeks and Hettiarachchi, 2019). Benefits may be greatest in phosphorus-fixing soils, degraded soils with low biological activity, and systems containing substantial legacy phosphorus. However, responses are likely to be smaller in soils where phosphorus is already adequate or where other nutrients, water or disease are the principal limitations.

Living phosphorus biofertilizers may also influence nutrient interactions, water relations and root architecture through biochar and microbial effects. These secondary benefits could improve resilience under drought or other stress, but they should be measured separately from phosphorus effects. Extension recommendations must avoid attributing all crop responses to phosphorus mobilization when changes in pH, potassium, micronutrients or water availability may also contribute Abou-Seeda et al., 2020).

Environmental implications

Environmental benefits are plausible when the technology reduces excess mineral-phosphorus application, retains soluble phosphorus and improves recovery. Biochar can also contribute to stable soil carbon, although climate benefits depend on feedstock sourcing, production emissions, transport and long-term stability (Lehmann et al., 2021). Environmental assessment should therefore include life-cycle boundaries rather than considering soil carbon alone. Potential risks also require attention. Phosphorus-rich biochar can release phosphorus rapidly under some conditions; poorly produced char may contain salts, heavy metals or organic contaminants; and microbial inoculants require biosafety screening. Enhanced mobilization of legacy phosphorus could increase loss risk if crop uptake does not match release. Field trials should monitor runoff or leaching where relevant, particularly in high-phosphorus soils and sloping landscapes.

Economic evaluation and the Functional Phosphorus Cost Index

Farmers evaluate technologies through cash cost, labor, reliability, compatibility with existing practices and expected return (Masere and Worth, 2022). Biochar production can be inexpensive when residues and efficient local equipment are available, but it can also be costly when feedstock collection, controlled pyrolysis, grinding, sterilization, inoculation, packaging and quality testing are included. Microbial products also require cold-chain or storage management in some cases. Economic claims should therefore be based on actual product and service costs rather than assumed values.

The Functional Phosphorus Cost Index is retained as a conceptual decision-support metric that relates the cost of a phosphorus-management option to the amount of plant-available phosphorus recovered by the crop. It is expressed as: Functional Phosphorus Cost Index = total cost per unit area ÷ plant-available phosphorus recovered per unit area. The index is useful only when both cost and recovery are measured under comparable field conditions. It should not be interpreted as a commercial estimate for a technology that has not yet been validated.

Table 2 illustrates how recovery assumptions change the amount of functional phosphorus generated from the same nominal input. It deliberately excludes product prices because no validated market cost for the proposed formulation is available. Future studies should replace assumptions with measured crop recovery, yield response, partial budgets, sensitivity analysis and, where relevant, life-cycle costing.

Commercialization and Quality-Assurance Pathways

Commercialization requires a reproducible product rather than a promising laboratory mixture. The formulation must maintain microbial viability, physical uniformity and predictable phosphorus behavior during manufacture, transport, storage and application. Critical specifications include feedstock origin, pyrolysis conditions, particle size, moisture, pH, electrical conductivity, nutrient content, contaminant limits, microbial identity, viable count, purity, shelf life and compatibility with the intended application equipment. Product format should follow agronomic need rather than marketing preference. Granules may be suitable for soil placement and blending; powders may support seed or root-zone application but can create dust; and liquid or suspension products may be compatible with fertigation only if particle settling, nozzle blockage and microbial stability are controlled. Seed coatings can establish microorganisms near emerging roots but require evidence that the coating process and storage do not reduce germination or viability.

Regulation is likely to be complex because the product may function simultaneously as a fertilizer, microbial inoculant and soil amendment. Regulators need clear evidence of identity, safety, composition, efficacy and label accuracy. A tiered system could allow provisional registration for restricted crops or regions after controlled trials, followed by broader claims when multi-location evidence becomes available. Independent quality testing and batch traceability are essential for farmer confidence.

Commercial models should also define who provides technical support. A biologically active product may fail when applied at the wrong time, stored in heat or combined with incompatible pesticides. Suppliers should therefore be accountable for training distributors and extension agents, providing simple instructions and responding to field-performance complaints. Public research institutions can contribute independent validation, while private firms provide production and distribution capacity.

Table 2. Conceptual illustration of phosphorus recovery from a common application rate. Values are illustrative and are not commercial recommendations.

Scenario	P_2O_5 supplied (kg acre^{-1})	Assumed recovery (%)	Plant-available P_2O_5 recovered (kg acre^{-1})	Interpretation
Conventional baseline	23.0	25	5.75	Illustrative recovery within the commonly reported first-season range.
Improved system: low response	23.0	35	8.05	Modest improvement requiring field confirmation.
Improved system: medium response	23.0	45	10.35	Substantial improvement; cost-effectiveness still unknown.
Improved system: high response	23.0	60	13.80	Optimistic scenario for sensitivity analysis, not a validated claim.

Note: The Functional Phosphorus Cost Index cannot be calculated responsibly until field-validated costs and phosphorus recovery data are available for the same crop, soil, season and application method.

Extension and Advisory Implications

Communicating the concept to farmers

Extension agents should explain living phosphorus biofertilizers through farm-level problems rather than technical terminology. The central message is that much soil phosphorus is present but poorly available, and the product is intended to help retain and mobilize phosphorus near the root. It should be presented as one component of integrated soil fertility management, not as a guaranteed replacement for all mineral fertilizer. Farmer education should emphasize five practical points: the product is biologically active and must be stored correctly; performance depends on soil and crop conditions; correct placement and timing are important; visible crop response may take time; and untreated comparison strips are useful for judging performance. Simple visual materials can show the difference between nominal fertilizer phosphorus and phosphorus actually recovered by the crop. Extension messages should also state where evidence is incomplete.

Participatory on-farm demonstration protocol

Participatory trials are necessary because farmer confidence is shaped by local evidence. Demonstrations should be co-designed with farmers and should compare treatments under the same management. At minimum, a trial should include the farmer's standard phosphorus practice, the living phosphorus biofertilizer with a reduced mineral-phosphorus rate, the biofertilizer alone where agronomically safe, and an untreated or low-phosphorus reference when ethical and practical. Plot size should be large enough for normal farm operations and repeated across representative farms.

Extension staff should record soil characteristics, product batch, application rate, timing, rainfall or irrigation, crop establishment, root observations, yield, phosphorus uptake where possible, labor and all input costs. Farmers should assess ease of use, perceived risk, compatibility with equipment and willingness to purchase. Demonstrations should continue for more than one season because biochar and microbial effects may change over time.

Decision-support tools

A farmer-facing decision tool should begin with eligibility rather than product promotion. Key questions include: Is soil phosphorus low or poorly available? Is the soil strongly acidic or calcareous? Is irrigation available? Which crop and application method are used? Has the product been validated in a comparable environment? What mineral-fertilizer reduction, if any, is supported by evidence? The tool should then provide a recommendation, uncertainty statement and monitoring plan. Digital tools can deliver soil-test interpretation, application reminders, batch information, short videos and two-way reporting. However, digital extension should complement rather than replace field support. Connectivity, language, literacy, device access and trust influence who benefits from digital agriculture (Klerkx et al., 2019; Fielke et al., 2020). Offline materials, voice messages and community demonstrations remain important, especially for farmers with limited access to smartphones or formal advisory services.

Table 3. Recommended protocol for extension-led on-farm evaluation of living phosphorus biofertilizers.

Stage	Recommended activity	Minimum evidence	Extension purpose
Pre-trial diagnosis	Soil test, farmer interview, field history and identification of the phosphorus constraint.	Baseline soil phosphorus, pH, crop practice and farmer objective.	Avoid testing the product where phosphorus is not the main limitation.
Treatment design	Compare farmer practice, integrated treatment, component controls where feasible and a reference treatment.	Documented rates, product batch and random or matched plot arrangement.	Separate product effect from fertilizer-rate and field-position effects.
Crop monitoring	Record emergence, vigor, root traits, stress, management events and adverse effects.	Standard observation dates and photographs or field sheets.	Provide timely advice and identify implementation problems.
Harvest and economics	Measure yield, quality, input use, labor and gross margin.	Comparable harvest area and complete cost record.	Translate biological performance into farmer-relevant value.
Farmer evaluation	Discuss usability, confidence, risk, willingness to pay and preferred support.	Documented feedback from women and men in different farm categories.	Guide product redesign and inclusive advisory messages.
Follow-up	Review residual effects and repeat performance in the next season.	At least two seasons where possible.	Assess reliability and longer-term soil response.

Adoption barriers, risk and social inclusion

Initial cost is a central adoption factor, but farmers also consider the possibility of yield loss if a familiar fertilizer rate is reduced. Introductory programs should therefore use gradual substitution, small trial areas, clear guarantees and transparent evidence. Credit or temporary vouchers may support learning, but long-term adoption will depend on reliable returns rather than permanent subsidy. Knowledge requirements can be higher than for conventional fertilizer because storage, biological viability and timing matter. Extension agents need training in soil fertility, microbial products and field diagnosis. Retailers should not be the only source of advice because sales incentives can encourage exaggerated claims. Independent extension and farmer organizations can provide a counterbalance.

Risk perception is shaped by product quality and past experience. A single ineffective batch can damage trust in the entire biofertilizer category. Certification, batch numbers, expiry dates, complaint mechanisms and visible quality-control seals are therefore adoption tools as well as regulatory tools. Extension programs should report negative and variable results, not only successful demonstrations. Gender and social equity require deliberate attention. Women farmers, tenants, smallholders and remote communities may have less access to land titles, credit, extension meetings, smartphones or input dealers. Demonstration locations, meeting times, language, trainer composition and payment models should be designed to include these groups. Sex-disaggregated participation and adoption data should be collected, consistent with the wider need for equitable access to agrifood-system innovations (FAO, 2023).

Extension delivery models

Participatory technology development is the most appropriate delivery model during early stages. Farmers, researchers, extension agents and manufacturers should jointly select application methods, evaluate field performance and modify product instructions. Farmer field schools can include modules on soil phosphorus, biochar quality, microbial viability, safe storage, trial design, record keeping and economic comparison. Learning should be based on field observation rather than one-way lectures. Public–private partnerships can combine independent validation with commercial logistics. Public extension services and universities can establish reference trials and training standards; private firms can manufacture and distribute products; farmer organizations can aggregate demand and feedback; and regulators can enforce quality. Contracts should protect the independence of trial reporting and require disclosure of product batches and financial interests.

An innovation-to-implementation cycle is therefore preferable to a linear laboratory-to-market model. Farmer feedback should return to researchers and manufacturers, and extension recommendations should change when performance differs across soils or seasons. This continuous learning approach is consistent with the broader role of extension as a knowledge and innovation system rather than a channel for technology transfer alone (Anderson and Feder, 2007; Davis et al., 2020).

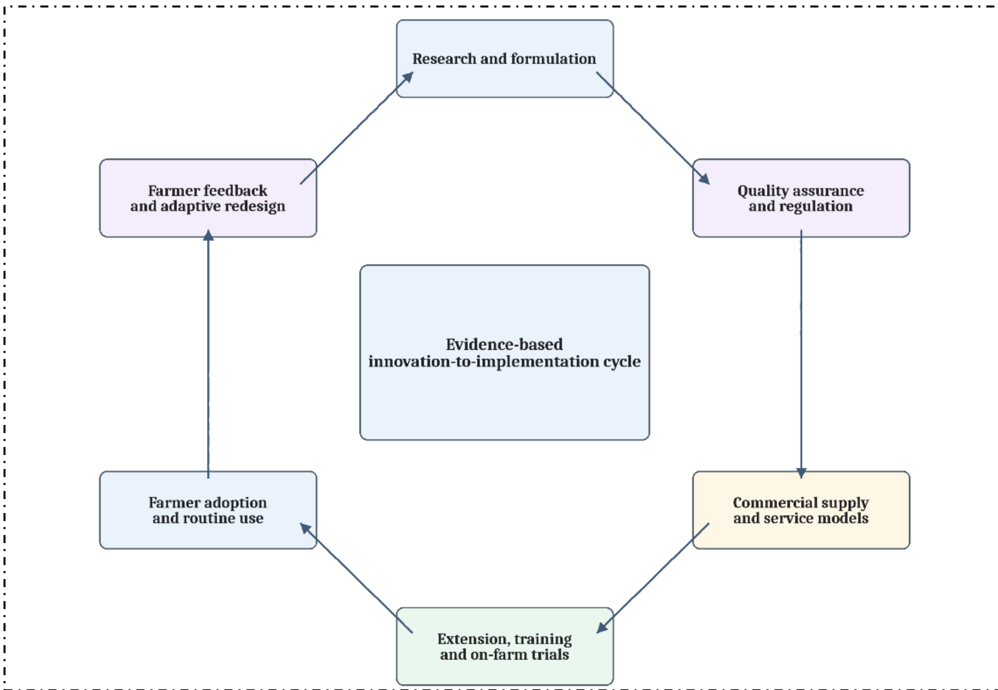

Figure 5. Innovation to implementation cycle for LPB extension and advisory pathways.

Table 4. Major adoption barriers and recommended extension responses.

Adoption barrier	Likely farmer concern	Recommended extension or institutional response
Up-front cost	The product may cost more than familiar fertilizer or require additional labor.	Use partial budgets, small trial areas, transparent pricing and evidence-based fertilizer-reduction guidance.
Performance uncertainty	Biological products may respond differently across soils and seasons.	Provide local multi-season demonstrations, comparison strips and clear uncertainty statements.
Knowledge and storage requirements	Incorrect storage or application may reduce viable organisms.	Train agents and retailers; use simple labels, expiry dates, voice or video guidance and follow-up visits.
Product quality	Farmers may encounter mislabeled or low-viability products.	Certification, batch traceability, independent testing and accessible complaint procedures.
Weak institutional support	Extension staff may lack soil and microbiology skills.	Develop accredited training, diagnostic tools and partnerships among universities, agencies and firms.
Gender and social exclusion	Women and resource-poor farmers may have limited access to information, credit and demonstrations.	Use inclusive scheduling, targeted outreach, women facilitators, group purchasing and sex-disaggregated monitoring.

Research Priorities

The first priority is formulation science. Research should identify biochar characteristics that support specific microbial strains, determine viable storage periods, test compatibility with fertilizers and pesticides, and establish release profiles for different phosphorus sources. Multi-omics tools can help identify mechanisms, but routine product development also requires practical measures of viable count, contamination and function.

The second priority is rigorous field validation. Trials should span soil types, crops, climates and seasons, include component controls and conventional-fertilizer benchmarks, and measure phosphorus uptake, yield, residual effects and environmental losses. Researchers should report null or negative outcomes and should avoid describing combined effects as synergistic unless interaction is tested statistically.

The third priority is economic and life-cycle assessment. Actual production, transport, storage, application and advisory costs are required to calculate the Functional Phosphorus Cost Index. Studies should include partial budgets, sensitivity to product price and yield variability, and distributional effects across farm sizes. Carbon benefits and environmental risks should be assessed over the full production chain.

The fourth priority is extension and adoption research. Farmer preferences, trust, gendered access, willingness to pay, retailer behavior and institutional capacity should be studied alongside agronomic performance. Randomized encouragement designs, participatory action research and longitudinal adoption studies could identify which delivery models produce sustained and equitable use.

Finally, standards and data reporting need improvement. Minimum datasets should include soil properties, biochar characterization, microbial identity and viable count, formulation storage, application details and adverse effects. Shared protocols would improve comparability and accelerate evidence-based regulation.

CONCLUSIONS

Living phosphorus biofertilizers offer a useful framework for integrating biochar engineering, microbial phosphorus mobilization and agricultural extension. The concept addresses a genuine need: phosphorus fertilizers are costly and inefficiently recovered, while many soils contain substantial phosphorus that is poorly available to crops. Evidence supports the capacity of biochar to influence phosphorus retention and soil conditions and of microorganisms to mobilize mineral and organic phosphorus. Selected combined systems have improved microbial persistence, phosphorus availability and crop performance.

The integrated technology is nevertheless not yet a universally validated replacement for mineral phosphorus fertilizer. Its responsible development requires standardized formulations, biosafety and quality assurance, multi-location field trials, realistic economic evaluation and soil-specific recommendations. Unsupported claims about recovery efficiency or cost reduction should be avoided until measured data are available.

Agricultural extension is central to this development process. Extension agents can translate the concept into practical messages, organize participatory comparison trials, support farmer decision-making and return field evidence to researchers and manufacturers. Public–private collaboration can facilitate production and distribution, but independent validation and inclusive access are essential. The most credible pathway is therefore not the promotion of a finished product, but a continuous science-to-farm learning cycle that gradually establishes where, how and for whom living phosphorus biofertilizers provide reliable value.

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