



Soil Phosphorus in Arid Agriculture: The Riddle Beneath Our Feet

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Abstract: Phosphorus (P) remains a persistent nutritional constraint in agriculture despite the accumulation of substantial native and fertilizer-derived P reserves in many cultivated soils. This contradiction is particularly pronounced in hot arid regions, where crops frequently experience P deficiency despite the presence of appreciable total and residual soil P. This opinion paper argues that the central challenge is not simply P scarcity, but P accessibility, governed by the interaction of alkaline soil chemistry, calcium carbonate, low organic carbon, moisture limitation, restricted diffusion, and weak biological turnover. In calcareous soils, soluble orthophosphate may progressively enter calcium-associated pools, to precipitate rapidly with calcium carbonate or get sorbed onto mineral surfaces forming insoluble calcium phosphate compounds while carbon and water limitations restricting ion diffusion as well as constrain microbial mineralization and rhizosphere-mediated mobilization. Thus, the conventional strategy of repeatedly increasing soluble P inputs may enlarge soil P stocks without proportionately improving crop acquisition. We propose a conceptual shift from chemical saturation to ecological mobilization, supported by three complementary strategies: (i) biological acceleration through native phosphate-solubilizing microorganisms, root mediated organic acids and arbuscular mycorrhizal fungi; (ii) rebuilding the organic and biological components of the P cycle through organic amendments, humic acids, biochar and adapted vegetation; and (iii) precision spatial and temporal synchronization of P supply with root activity and soil moisture. The paper further emphasizes that residual soil P is not a homogeneous reserve: its contribution depends on the balance between mineral stability, release kinetics, diffusion, biological transformation, and plant uptake. Future research should, therefore, move beyond static estimates of available P toward fraction-specific and process-oriented assessment of P accessibility. For hot arid agroecosystems, sustainable P management will require integrating fertilizer inputs with the biological and ecological processes that govern the mobilization and recycling of existing soil P reserves.

Key words: Arid soils, phosphorus accessibility, residual soil phosphorus, calcareous soils, microbial mobilization, phosphorus cycling; precision

nutrient management.

Phosphorus (P) management in arid agriculture presents a fundamental challenge: soils may contain appreciable quantities of native and fertilizer-derived phosphorus, yet crops continue to suffer from inadequate P nutrition. This apparent contradiction reflects the complex interactions among soil chemistry, moisture availability, organic matter dynamics and biological activity that regulate the release and acquisition of P. Under the alkaline and frequently calcareous conditions of hot arid regions, these interactions become particularly important, as the presence of phosphorus in soil does not necessarily ensure its timely availability to plants. Understanding this distinction is essential for developing more efficient and sustainable strategies for phosphorus management in arid agroecosystems.

Phosphorus scarcity is fundamentally a problem of accessibility in agricultural lands

Phosphorus scarcity is one of the enduring paradoxes of modern agriculture. Although P is essential for plant growth, energy transfer, nucleic acid synthesis, and root development, only a small fraction of total soil P is present in forms immediately accessible to plants. The concentration of orthophosphate ions in soil solution is generally extremely low often 0.001 mg L^{-1} to 1 mg L^{-1} with an average around 0.05 mg L^{-1} and in arid soil solution often ranging from less than 0.01 mg L^{-1} to few milligrams per litre, because phosphorus binds with calcium and other minerals and is continuously partitioned between solution and solid phases. Consequently, crop production has historically depended on repeated fertilizer application to maintain an adequate concentration of P near plant roots. This approach, however, has created a contradiction. Large quantities of fertilizer-derived and native P have accumulated in agricultural soils, yet crops frequently experience P deficiency. Soil P therefore represents both a nutrient reserve and a chemical sink. Broadly, soil P occurs as inorganic P (Pi) and organic P (Po), distributed among soluble, weakly associated, mineral-bound, occluded, and biologically transformed pools. These pools differ substantially in their chemical stability and potential accessibility. The dominant processes controlling P retention depend strongly on soil properties. In acidic

soils, phosphate is commonly retained through reactions with iron and aluminium oxides. In alkaline and calcareous soils, precipitation and association with calcium become increasingly important. Over time, relatively reactive phosphate forms may become incorporated into more stable mineral phases. Organic P is simultaneously regulated by plant residues, microbial biomass, enzymatic hydrolysis, and sorption reactions.

Thus, the problem of soil P cannot be understood simply in terms of total concentration. A soil containing substantial total P may still support poor crop growth if the exchange between solid-phase reserves and the soil solution is too slow to meet plant demand. This distinction between P quantity and P accessibility is particularly important in arid agriculture where free concentration of orthophosphate ions (H_2PO_4^- and HPO_4^{2-}) remains restricted due to high pH. Here, the biogeochemical environment restricts both the chemical release and biological turnover of P. Residual soil phosphorus should therefore be viewed not merely as a historical consequence of fertilizer accumulation but as a heterogeneous reserve whose accessibility depends on mineralogy, organic matter, soil moisture, roots, organic acid concentration and microbial activity. The central question for arid agriculture is consequently not only how much P exists in the soil, but which fractions can potentially contribute to plant nutrition, under what environmental conditions, and through which biological or agronomic interventions. Consequently, sustainable P management requires a shift from simply increasing soil P stocks toward understanding and enhancing the accessibility and flux of residual P to plant roots. This challenge becomes especially critical in hot arid agro-ecosystems, where alkaline, calcareous, carbon-poor and moisture-limited conditions intensify P immobilization and constrain its biological turnover.

The apatite-carbon paradox and the phosphorus pool dilemma in arid lands

The hot arid regions of north-western India, particularly the Thar Desert, provide an extreme example of the mismatch between total soil P and plant availability. These landscapes are characterized by coarse-textured soils, alkaline reaction, variable calcium carbonate content,

low organic carbon, high temperature, erratic rainfall, and prolonged periods of soil moisture deficit. Such conditions collectively create a distinctive environment for P immobilization. The geochemical component of this dilemma can be described as an apatite-carbon paradox (a substantial mineral-associated P reserve, limited organic carbon, and insufficient biological activity to mobilize that reserve at a rate matching crop demand). Alkaline and calcium-rich conditions favour the retention of P in calcium-associated mineral phases. Soluble orthophosphate introduced through fertilizers may initially react with calcium and carbonate-rich soil environments and subsequently become associated with increasingly stable calcium phosphate minerals. Consequently, repeated application of soluble P may enlarge the total soil P reserve without proportionally increasing the biologically accessible pool. However, chemical immobilization alone does not explain the persistence of P deficiency. The rapid chemical fixation and low moisture content limiting ion diffusion. Arid soils are also frequently poor in soil organic carbon. Low carbon availability limits microbial biomass and restricts the production of organic acids, phosphatases, phytases, and other biochemical agents involved in P cycling. Prolonged dry periods further constrain microbial activity and reduce the continuity of water films required for diffusion of phosphate ions toward plant roots.

This produces a double constraint. First, P is retained chemically in relatively stable mineral forms. Second, the biological mechanisms capable of mobilizing or mineralizing these reserves are weakened by carbon and moisture limitations. Even when potentially mobilizable P exists, plant roots may be unable to access it because diffusion is severely restricted under dry conditions. The organic P pool presents an additional dimension. Organic P compounds, including inositol phosphates and other phosphor-monoesters, may represent an important component of total P reserves. Their contribution to plant nutrition depends on biological mineralization through organic acids, phosphatase and phytase activity. In carbon-poor and moisture-stressed environments, this biological recycling pathway may remain weak for extended periods. The result is a P pool paradox: arid soils may contain appreciable total

and residual P reserves while simultaneously functioning as P-deficient production systems. The scarcity experienced by crops is therefore not necessarily evidence of elemental absence. Rather, it reflects the combined consequences of mineral stabilization, low biological turnover, restricted diffusion, and environmental desynchronization between rainfall, microbial activity, root activity and crop demand. Thus, recognizing this distinction is essential because it shifts the scientific objective from simply adding more fertilizer toward understanding how existing P reserves can be assessed, protected, and selectively mobilized.

Fallacies in conventional phosphorus management in arid lands

Conventional P management has largely been built around the assumption that crop P deficiency can be overcome through repeated application of soluble fertilizers. While such fertilizers remain important, this strategy becomes increasingly inefficient when applied without regard to the biogeochemical constraints of arid soils. The first fallacy is the assumption that greater fertilizer input necessarily produces proportionately greater P availability. In calcareous soils, increasing the concentration of soluble P can also increase the opportunity for precipitation and retention reactions or chemical fixation. Repeated fertilization may therefore build residual P stocks without ensuring efficient recovery by crops. The second limitation is the widespread use of blanket application strategies. Surface broadcasting distributes P across a large volume of reactive soil, increasing contact with calcium carbonate and other retention surfaces. In arid environments, this problem is compounded by low moisture, which restricts movement of P toward roots. More precise placement may therefore be more important than simply increasing application rates. A third weakness is the reliance on static indicators of soil P availability that only quantify of readily accessible or extractable phosphorus at a given time. Conventional extractants provide valuable information about operationally defined pools, but a single estimate of available P cannot fully represent the capacity of soil to replenish P in the rhizosphere. Particularly in arid soils, accessibility depends on transient interactions among mineral surfaces, organic

matter, microbial activity, roots, organic acid concentration and moisture content.

There is also a tendency to treat residual or legacy P as either permanently unavailable or automatically available to crops. Both assumptions are problematic. Residual P is heterogeneous. Some fractions may remain strongly stabilized, whereas others may contribute to plant nutrition under favourable biological and environmental conditions. The challenge is therefore to identify the fractions with meaningful accessibility potential rather than treating the entire residual pool as a uniform resource. The conventional paradigm has generated another unintended consequence: the biological dimension of P cycling has often received less attention than fertilizer chemistry. Yet plants and microorganisms possess mechanisms capable of altering the rhizosphere environment. Organic acid exudation, proton release, enzymatic hydrolysis, microbial turnover, and mycorrhizal exploration can influence the accessibility of both inorganic and organic P. This does not imply that biological approaches can universally replace mineral fertilizers. Rather, it suggests that P management in arid lands should move beyond the binary choice between chemical and biological inputs. The more productive question is how these components can be integrated to improve recovery of both applied and residual P.

A strategic framework for unlocking residual phosphorus in arid lands

We propose that sustainable P management in arid lands should be built around an integrated framework of biological acceleration, organic activation, and precision delivery.

i. Real-time assessment of operational P pools in arid lands: Conventional soil P assessment largely relies on static chemical indices such as Olsen-P, which provide a snapshot of extractable P but inadequately represent the dynamic, operationally accessible P pools that fluctuate with moisture, microbial activity, root exudation and organic matter turnover. This methodological gap is particularly important for arid lands, where residual P may remain chemically protected yet potentially reversible under favourable biological and hydrological conditions. Hence, the future assessment should integrate sequential P fractionation with real-

time measurements of soil solution P, microbial biomass P, phosphatase/phytase activity, P-solubilizing microbial abundance, root activity and rhizosphere processes. Coupling these measurements with moisture pulses and plant P uptake could identify reversible-accessible soil P (RASP) that can be transiently mobilized and recaptured by crops rather than considered permanently unavailable. Such an approach would shift P management from measuring *what is extractable* to determining what can become accessible, when, and through which biological pathway.

ii. Biological acceleration through native microorganisms: Arid ecosystems harbour microorganisms adapted to repeated cycles of heat, drought, salinity, and nutrient scarcity. Native phosphate-solubilizing bacteria and fungi may therefore offer advantages over generic inoculants developed under favourable laboratory conditions. Their potential functions include, organic acid production, localized acidification, calcium complexation, and enzymatic mineralization of organic P. Arbuscular mycorrhizal fungi (AMF) provide a complementary mechanism. Their hyphal networks extend beyond the immediate root depletion zone and can improve exploration of diffusion-limited nutrients. In dry soils, where P mobility is inherently restricted, this extended absorptive network may be particularly important. The future emphasis should be on functional microbial consortia rather than individual organisms alone. The effectiveness of such systems must, however, be evaluated under realistic field conditions, because microbial performance depends strongly on carbon availability, soil moisture, soil pH, temperature, crop genotype, and indigenous microbial competition.

iii. Rebuilding the organic component of the P cycle: Another strategy is to address carbon limitation. Organic amendments can provide substrates for microbial activity while influencing mineral surfaces and rhizosphere chemistry. Compost, farmyard manure, crop residues, and other locally available organic resources may therefore support both biological P turnover and soil physical improvement. Humic acids block fixation sites improving the pool of available P over time. Traditional arid-land vegetation systems deserve renewed attention, for example *Prosopis cineraria* (Khejri)

based agro-forestry system may contribute to nutrient cycling through deep rooting, litter deposition, and rhizosphere modification. Such systems should not be viewed merely as agroforestry structures but as potential biological components of nutrient redistribution. Deep-rooted vegetation may connect subsoil mineral reserves with biologically active surface processes, although the magnitude and mechanisms of this contribution require further experimental quantification. Low-grade rock phosphate combined with organic and mineral materials also represents a potential alternative to exclusive dependence on highly soluble fertilizers. The rationale is not that rock phosphate will universally perform better, but that organic decomposition and localized microbial activity may create conditions favourable for gradual dissolution and synchronized nutrient release. Biochar also promotes the shift from stable or organic P into inorganic, plant accessible forms.

iv. Precision spatial and temporal management: The fourth component is to reduce unnecessary contact between applied P and reactive soil surfaces. Subsurface band placement near the active root zone can concentrate P where crop demand is greatest and where soil moisture persists longer. Biological activity, P diffusion, and root growth are strongly influenced by moisture pulses. Management interventions should therefore consider rainfall timing and the short periods during which microbial and root activity are simultaneously favourable. The objective is not to eliminate fertilizers but to improve the efficiency of the entire P cycle. Applied P, residual P, organic matter, microorganisms, roots, and moisture should be treated as interacting components rather than independent management variables. In irrigated systems, carefully managed fertigation may further synchronize P supply with crop demand. Temporal synchronization is equally important in rainfed agriculture. For rainfed pearl millet, clusterbean and moth bean, localized placement near the root zone and synchronization with monsoon rainfall can improve P-use efficiency by matching P release with moisture availability and crop demand. In irrigated systems, band placement or fertigation-based application may further reduce fixation losses.

v. Development and use of green phosphatic fertilizers: Green phosphatic fertilizers (GPF) represent an emerging approach for improving P delivery through combinations of mineral, organic, microbial and nanotechnology-based components. It is eco-friendly, slow release bio-based phosphorus with microbial inoculants. A promising formulation can integrate locally available low-grade rock phosphate, organic amendments, phosphate-solubilizing microorganisms (PSM), phytase enzymes and nano-phosphate carriers, thereby converting relatively unavailable P resources into more efficiently deliverable forms. It not only designed to nourish crops but also protecting soil health. Phytase-enriched green fertilizers are particularly relevant for mobilizing phytate-bound P. Incorporating phytase-producing microorganisms or stabilized phytase into an organic matrix can hydrolyse phytate and release orthophosphate progressively. Encapsulation of phytase and P-mobilizing microorganisms within biodegradable organic or polymeric carriers could protect the bioactive components during storage and enable their controlled release in the rhizosphere. Similarly, nano-phosphates may provide a high-reactivity P source with controlled dissolution and improved spatial delivery, particularly when integrated with organic or microbial carriers. It also helps to increase P use efficiency. Future development should therefore focus on multifunctional formulations combining P source + organic carrier + phytase/PSM + nano-delivery system. Their performance should be evaluated for P release kinetics, enzyme and microbial stability, plant P uptake, agronomic efficiency, residual P availability and environmental safety. Such formulations could provide a resource-efficient pathway towards next-generation green P fertilization. Thus, GPFs can transform indigenous P resources into a locally adapted, circular and biologically mediated fertilizer strategy for resilient arid-land agriculture.

Policy and research agenda

A transition toward biologically inspired P management requires changes in both research priorities and agricultural policy.

- Soil testing should evolve beyond a single static estimate of extractable P. Routine tests will remain essential, but research programs

should develop complementary approaches capable of identifying important mineral and organic P fractions and their potential contribution to crop nutrition. The goal should be to distinguish between total P abundance and functionally relevant accessibility.

- Crop improvement programs should give greater attention to below-ground traits. Root architecture, root biomass, rhizosphere acidification, organic anion release, enzyme and microbial activity, and mycorrhizal responsiveness may influence P acquisition under arid conditions. Traditional dryland crops such as pearl millet, clusterbean, and moth bean provide valuable genetic resources for exploring such traits.
- Microbial technologies should prioritize locally adapted organisms and multi-location field validation. The question is not simply whether a microorganism can solubilize phosphate *in vitro*, but whether it can persist and function under fluctuating temperature, moisture, carbon conditions and natural pool of organic P available for mineralization.
- Agricultural extension should promote precision placement and integrated nutrient management rather than uniform fertilizer recommendations. Smallholders require practical technologies such as seed-cum-fertilizer drills, localized organic application methods, and reliable microbial formulations.
- Future research must explicitly examine the sustainability of residual P mobilization. Important questions include: How much residual P can contribute to crop nutrition? Which fractions are most responsive to biological intervention? How long can reduced fertilizer inputs be sustained? Under what conditions does mobilization create environmental risks? These questions require long-term field experiments linking P fractions, biological activity, crop uptake, and environmental loss pathways.
- Artificial intelligence (AI) may play a revolutionary role in optimizing phosphorus solubilizing microorganisms, smart bio-sensing, predicting soil insights, understanding root systems architecture engineering and precision agriculture for P nutrition.

Conclusions

The phosphorus problem of arid agriculture is not simply a problem of insufficient fertilizer but it is a problem of biogeochemical accessibility. Beneath apparently P-deficient crops may lie substantial reserves of mineral and organic phosphorus whose contribution to plant nutrition is constrained by alkaline chemistry, calcium carbonate, carbon scarcity, moisture limitation, and weak biological turnover. The conventional response of increasing soluble fertilizer inputs alone cannot resolve this contradiction. A more effective strategy must integrate the management of applied P with the ecological processes governing residual soil phosphorus. Native microorganisms, mycorrhizal networks, organic amendments, adapted agroforestry, efficient crop genotypes, and precision nutrient placement collectively offer opportunities to improve this integration. The proposed transition is therefore from chemical saturation toward ecological mobilization. Residual P should not be regarded simply as an inert historical accumulation, nor should it be assumed to be freely available. It should be understood as a heterogeneous soil resource whose accessibility can vary according to mineral composition, biological activity, root processes, and environmental conditions.

For the hot arid regions of north western India, a desert-specific P strategy should combine fraction-oriented soil assessment with field-based understanding of biological mobilization and precision agronomy. Ultimately, solving the phosphorus riddle beneath our feet will depend on changing how soil P is perceived. As phosphorus is highly reactive and binds tightly to create an insoluble “phosphorus prison”. The goal should no longer be merely to add more phosphorus to the soil. Instead, agricultural science must learn how to manage the phosphorus already present, transforming soil from a passive chemical sink for fertilizers into a biologically active system capable of recycling one of agriculture’s most critical finite and endanger nutrient.

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J.C. Tarafdar is an eminent soil biologist known for his pioneering contributions to soil biology, phosphorus nutrition, and agricultural nanotechnology, particularly in arid and semi-arid agro-ecosystems. He served as an ICAR National Fellow at CAZRI during 1999–2014 and subsequently as an ICAR Emeritus Scientist and UGC Emeritus Professor. His research has advanced the understanding of native soil phosphorus mobilization and soil–plant–microbe interactions. He has also pioneered the development of biosynthesized nanonutrients and nano-induced polysaccharide formulations for agricultural applications. His international academic engagements include Alexander von Humboldt and DAAD fellowships in Germany. He is a Fellow of the National Academy of Agricultural Sciences (NAAS) and the Indian Society of Soil Science (ISSS).

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