International
Journal of Agriculture Innovations
and Cutting-Edge Research

Phosphorus Dynamics and Management Strategies in Alkaline Calcareous Soils of Pakistan: Challenges, Opportunities, and Future Directions

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Abstract

Phosphorus (P) is the second most important macronutrient limiting crop productivity in Pakistan, yet phosphorus use efficiency (PUE) remains low because of the widespread occurrence of alkaline calcareous soils. Approximately 70% of Pakistan's cultivated soils are calcareous, characterized by high pH, calcium carbonate content, and low organic matter levels, which promote P-fixation and reduce its availability to plants. Consequently, a large proportion of applied P is converted into insoluble calcium-phosphate compounds, often limiting fertilizer recovery efficiency to less than 20%, increasing production costs, and contributing to environmental concerns associated with excessive fertilizer application. This review critically evaluates recent advances in improving phosphorus use efficiency (PUE) in alkaline calcareous soils and identifies sustainable management strategies suitable for Pakistan. Relevant peer-reviewed literature published between 2020 and 2026 was systematically analyzed, focusing on P dynamics, fertilizer management practices, soil amendments, crop responses, and emerging technologies under alkaline calcareous soil conditions. The reviewed studies demonstrate that integrated approaches involving phosphate-solubilizing bacteria, arbuscular mycorrhizal fungi, organic amendments, integrated nutrient management, biochar application, foliar phosphorus fertilization, precision nutrient management, and P-efficient crop cultivars can substantially enhance P availability, uptake, and crop productivity compared with conventional fertilization practices. Despite these advances, important knowledge gaps remain regarding long-term field validation, economic viability, site-specific recommendations, and large-scale adoption across diverse farming systems. Overall, the available evidence indicates that integrated biological and agronomic P management strategies represent the most promising pathway for improving PUE, sustaining soil fertility, reducing dependence on mineral fertilizers, and enhancing agricultural productivity in Pakistan. Strengthened investments in research, extension services, and farmer-oriented P-efficient technologies are essential for achieving sustainable nutrient management and national food security.

Keywords: Phosphorus use efficiency; Calcareous soils; Phosphate-solubilizing bacteria; Arbuscular mycorrhizal fungi; Integrated nutrient management; Biochar; Sustainable agriculture; Pakistan.

CrossRef. DOI:	10.67244/jai.bwo-researches.v4i2.a256
Journal Link:	https://jai.bwo-researches.com/index.php/jwr/index
Paper Link:	https://jai.bwo-researches.com/index.php/jwr/article/view/256
Publication Process	Received: 08 June 2026/ Revised: 15 June 2026/ Accepted: 22 June 2026/ Published: 30 June 2026
ISSN:	Online [3007-0929], Print [3007-0910]

Publisher: BWO Research International (15162394 Canada Inc.) https://www.bwo-researches.com

Introduction

Phosphorus (P) is an essential macronutrient involved in energy transfer, nucleic acid synthesis, photosynthesis, root development, and grain formation. Its deficiency restricts plant growth, causing poor root development, delayed maturity, reduced biomass, and significant yield losses (Khan et al., 2023; Pisa et al., 2022). Beyond its agronomic importance, P management has emerged as a global sustainability challenge because phosphate rock is a finite, non-renewable resource. Consequently, improving PUE and promoting circular phosphorus use through recycling and recovery have become major priorities. In Pakistan, P deficiency is among the most widespread constraints to agricultural productivity. Although calcareous soils often contain 200–800 mg P kg^{-1}, only a small proportion is plant-available (Jalali et al., 2023). Approximately 80–95% of agricultural soils are deficient in available P, while most contain less than 1% organic matter, further limiting nutrient cycling and P availability (Nasir et al., 2024). The predominance of alkaline calcareous soils, characterized by high pH, high calcium carbonate content, and low organic matter, promotes P fixation through the formation of sparingly soluble calcium-phosphate compounds (Adnan et al., 2025). As a result, only 10–25% of applied P fertilizer is utilized by crops, while the remainder becomes immobilized, leading to low PUE and poor economic returns (Jamal et al., 2023).

Similar challenges occur in other calcareous-soil regions, including China, India, Australia, and North Africa, where approaches such as precision nutrient management, biofertilizers, organic amendments, microbial inoculants, and P-efficient crop cultivars have improved P recovery and availability. These experiences provide valuable guidance for Pakistan's phosphorus management strategies. Recent efforts to improve PUE have focused on biological, agronomic, genetic, and technological interventions, including P-solubilizing microorganisms, arbuscular mycorrhizal fungi, integrated nutrient management, organic amendments, biochar, foliar P application, precision fertilization, and P-efficient cultivars. However, information remains fragmented, and a comprehensive evaluation of these approaches under Pakistan's calcareous soil conditions is still needed. Therefore, this review synthesizes recent advances in improving PUE in Pakistani calcareous soils by examining P dynamics and fixation mechanisms, evaluating biological and agronomic interventions, assessing lessons from other calcareous-soil regions, identifying research gaps and future opportunities, and providing science-based recommendations to enhance fertilizer recovery, crop productivity, circular P management, and long-term sustainability (Khan et al., 2023; Pisa et al., 2022; Jalali et al., 2023; Nasir et al., 2024; Adnan et al., 2025; Jamal et al., 2023).

Annexure (A)

Methodology of Literature Review

This review was conducted using a structured literature search and screening approach to synthesize recent advances in improving phosphorus use efficiency (PUE) in calcareous soils, with particular emphasis on Pakistan and comparable agro-ecological regions. The review focused on biological, agronomic, genetic, and technological strategies aimed at enhancing phosphorus availability, uptake, and utilization under alkaline soil conditions.

Relevant literature was retrieved from four major scientific databases: Scopus, Web of Science, ScienceDirect, and Google Scholar. These databases were selected because of their extensive coverage of agricultural, soil, environmental, and plant sciences. A comprehensive search was performed using combinations of keywords including "phosphorus use efficiency," "phosphorus fixation," "calcareous soils," "alkaline soils," "phosphate-solubilizing bacteria," "arbuscular mycorrhizal fungi," "integrated nutrient management," "biochar," "organic amendments," "precision nutrient management," "foliar phosphorus application," "phosphorus-efficient cultivars," "wheat," "maize," and "Pakistan." Boolean operators (and, or) were used to refine the search and improve the relevance of retrieved studies. The review primarily considered publications published between 2020 and 2026 to capture recent developments in phosphorus management and sustainable agriculture. However, selected foundational studies published before 2020 were also consulted where necessary to explain key concepts related to phosphorus chemistry, fixation mechanisms, and plant nutrition.

Characteristics of Alkaline Calcareous Soils in Pakistan

Alkaline calcareous soils dominate much of Pakistan's cultivated land and are primarily classified as Aridisols and Entisols, reflecting the country's arid and semi-arid climate. Low rainfall, high evapotranspiration, and limited leaching promote calcium carbonate accumulation, resulting in soils with high pH (7.5–8.5 or higher), elevated carbonate content, low organic matter, and poor nutrient availability, particularly phosphorus (P) (Waheed and Muhammad, 2021). High soil pH influences nutrient solubility, microbial activity, and overall soil fertility (Hussain et al., 2026). A defining feature of these soils is their high calcium carbonate content (3–25%), which promotes the conversion of soluble P into sparingly soluble calcium-phosphate minerals such as dicalcium phosphate, octacalcium phosphate, tricalcium phosphate, and hydroxyapatite. Consequently, a large proportion of applied P becomes fixed and unavailable to plants (Habraken et al., 2016).

Low soil organic matter (<1% in most cultivated soils) further limits P availability by reducing microbial activity, nutrient cycling, and the production of organic compounds that help mobilize fixed P (Sabah et al., 2022). As a result, P deficiency remains one of the most severe fertility constraints in Pakistan. Although total soil P reserves may be substantial, nearly 90% of soils are deficient in available P, and crops typically recover only 15–20% of applied P fertilizer, with the remainder becoming immobilized in insoluble forms (Aimen et al., 2022). High pH and low organic carbon also restrict microbial activity, reducing nutrient mineralization and P solubilization. Therefore, sustainable approaches such as phosphorus-solubilizing bacteria (PSB), arbuscular mycorrhizal fungi (AMF), and organic amendments are increasingly being explored to improve P availability and nutrient cycling in calcareous soils (Tang et al., 2024).

Overall, Pakistan's alkaline calcareous soils are characterized by high pH, elevated calcium carbonate, low organic matter, poor P availability, strong P fixation, and limited biological activity, all of which reduce nutrient-use efficiency and crop productivity. Sustainable phosphorus management is therefore essential for improving soil fertility, enhancing PUE, and supporting long-term agricultural productivity (Waheed and Muhammad, 2021; Hussain et al., 2026; Habraken et al., 2016; Sabah et al., 2022; Aimen et al., 2022; Tang et al., 2024).

Phosphorus Chemistry and Fixation in

Calcareous Soils

Improving PUE in alkaline calcareous soils requires understanding the dynamic processes that regulate P availability. Although soils contain substantial organic and inorganic P reserves, only a small fraction remains in the soil solution for plant uptake at any given time (Ahmad et al., 2022). Therefore, P availability depends on the balance among soil solution P, labile pools, and stable P fractions rather than total soil P content. In calcareous soils, high pH and calcium carbonate content promote phosphate adsorption and precipitation. Applied P is progressively transformed into less soluble calcium-phosphate minerals such as dicalcium phosphate (DCP), octacalcium phosphate (OCP), and hydroxyapatite (HAP), reducing its availability to plants (Shen et al., 2011). Elevated soil pH further enhances P fixation by increasing interactions between phosphate and calcium ions, resulting in low fertilizer recovery and PUE values of only 10–25% in Pakistan's calcareous soils (Pang et al., 2024; Ahmad et al., 2022).

Biological processes can partially overcome these constraints. Plant roots modify the rhizosphere through the release of organic acids, protons, and enzymes that increase P solubility, while phosphorus-solubilizing bacteria (PSB) and arbuscular mycorrhizal fungi (AMF) mobilize fixed and organic P through acidification, chelation, and enzymatic mineralization (Wahid et al., 2020; Hussain et al., 2021). AMF also enhances P uptake by extending hyphal networks beyond root depletion zones. However, high pH, low organic matter, limited carbon availability, and moisture stress often restrict microbial activity and reduce the effectiveness of biological interventions. Therefore, sustainable improvements in PUE require integrated management approaches that address both chemical fixation and biological P mobilization to enhance fertilizer recovery, reduce P losses, and sustain crop productivity in calcareous agroecosystems (Ahmad et al., 2022; Shen et al., 2011; Pang et al., 2024; Wahid et al., 2020; Hussain et al., 2021).

Annexure (B)

Concept of Phosphorus Use Efficiency

The term phosphorus use efficiency denotes the capability of crops to obtain, utilize, and convert applied P into an economic yield. PUE generally consists of two major components, including:

Phosphorus Acquisition Efficiency (PAE)

Phosphorus acquisition efficiency (PAE) refers to the ability of a plant to absorb P from soil and transport it to plant tissues. Therefore, plants exhibiting high PAE can absorb a higher quantity of P from the soil, thereby maintaining growth and productivity with lower fertilizer inputs. In this regard, the architecture of the root system determines the P acquisition efficiency. Soil P is considered an immobile element in soil. Therefore, an extensive plant root system with better root length and density is more efficient in exploring a greater volume of soil to reach P reserves within the soil (Lynch, 2019). A recent study showed that wheat genotypes revealed substantial differences in P acquisition efficiency among various cultivars grown in alkaline calcareous soil (Abbas et al., 2024). Root hairs facilitate the plant's access to P located in microsites due to a higher absorptive surface area, and the root hair density and length improve soil-root contact and decrease the P diffusion limitations, thereby enhancing P uptake under limited P supply (Brown et al., 2013).

Annexure (C)

Phosphorus Utilization Efficiency (PUE)

Phosphorus utilization efficiency (PUtE) is defined as the capacity of a plant to convert absorbed P into biomass and grain yield. It determines how the absorbed P is used in plant physiological and metabolic processes, which defines plant growth and productivity (Veneklaas et al., 2012). PUtE is influenced by many physiological mechanisms, including P remobilization in plants, allocation of P to active plant tissues, improved photosynthetic performance, and the capacity to regulate cellular functions under low soil P environments (Lynch, 2011). Therefore, greater PUtE supports plants to show better growth and yield under limited P uptake. Under P-deficient alkaline calcareous soils of Pakistan, the enhancement in PUtE is more important since a significant quantity of applied P gets fixed and becomes unavailable for plant uptake. The cultivars with superior P utilization efficiency under such conditions can achieve higher productivity with lower P (Richardson et al., 2011).

Annexure (D)

Current Status of Phosphorus Deficiency in Pakistan

Phosphorus deficiency is a major and persistent soil fertility constraint limiting agricultural productivity in Pakistan, particularly in alkaline calcareous soils where P availability and fertilizer-use efficiency are inherently low. The problem is further aggravated by low soil organic matter, imbalanced fertilizer use, inadequate soil testing, and poor nutrient management practices. Low soil organic matter (<1% in most agricultural soils) restricts microbial activity, nutrient cycling, and the mineralization of organic P into plant-available forms, thereby reducing both soil fertility and biological P mobilization (Jamal et al., 2023). As a result, P deficiency is widespread across major cropping systems, with significant yield responses to P fertilization reported in wheat, maize, chickpea, and oilseed crops, especially in intensively cultivated wheat-growing areas (Abbas et al., 2024). Fertilizer management practices further contribute to the problem. Farmers often prioritize nitrogen fertilizers because of their immediate and visible effects on crop growth, while P fertilizers are frequently applied at suboptimal rates due to their higher cost and rising fertilizer prices (Jamal et al., 2023). This nutrient imbalance reduces crop productivity, nutrient-use efficiency, and long-term soil fertility.

Limited adoption of soil testing and site-specific nutrient management also exacerbates P deficiency. Restricted access to soil testing facilities and inadequate awareness of balanced fertilization often lead to generalized fertilizer recommendations that fail to address field-specific soil conditions. Consequently, P fertilizers may be under-applied, causing nutrient deficiencies and yield losses, or applied inefficiently, reducing their economic and agronomic benefits. Despite increased P fertilizer consumption in recent decades, improvements in phosphorus use efficiency (PUE) remain limited. In calcareous soils, a large proportion of applied P becomes immobilized through adsorption and precipitation reactions, leaving only a small fraction available for plant uptake. This results in low crop P recovery, accumulation of fixed P in soils, increased production costs, and reduced fertilizer investment efficiency (Ahmad et al., 2022). Therefore, integrated P management strategies are needed to enhance P availability, improve fertilizer recovery, and support sustainable agricultural production in Pakistan.

Biological Approaches for Improving Phosphorus Use Efficiency

Phosphate-Solubilizing Bacteria (PSB)

Phosphate-solubilizing bacteria (PSB) have emerged as a promising biological strategy for enhancing P availability and PUE in the alkaline calcareous soils. These microorganisms convert insoluble P into plant-available forms through several mechanisms, including the secretion of organic acids, proton release, calcium ion chelation, and the production of phosphatase enzymes (Adnan et al., 2025). By modifying rhizosphere chemistry, PSB helps mobilize P that would otherwise remain unavailable to plants.

Several bacterial genera, including Bacillus, Pseudomonas, Enterobacter, and Rhizobium, have been identified as effective phosphate solubilizers (Hussain et al., 2021). These microorganisms colonize the rhizosphere and enhance P solubility, thereby improving nutrient uptake by crops. Recent studies have shown that PSB inoculation can increase phosphorus availability, promote plant growth, and improve crop productivity under calcareous soil conditions. In particular, the combined application of PSB and P fertilizers has been reported to improve wheat growth, grain yield, and PUE compared with conventional fertilization practices (Ahmad et al., 2022).

The effectiveness of PSB is largely attributed to their production of organic acids, such as oxalic, malic, citric, and gluconic acids, which lower rhizosphere pH, chelate calcium ions, and dissolve calcium-bound P compounds (Hussain et al., 2021). Although PSBs offer considerable potential for improving P availability, their performance may vary under field conditions. Therefore, their integration with other nutrient management practices is considered a more reliable approach for achieving sustainable improvements in PUE in Pakistan's calcareous soils.

Annexure (E)

Arbuscular Mycorrhizal Fungi (AMF)

The AMF are important soil microorganisms having the capacity to enhance P acquisition and PUE in alkaline calcareous soils. Actually, these fungi develop a symbiotic relationship with plant roots by forming hyphal networks, which accelerate nutrient uptake (Smith & Smith, 2011). Moreover, not only does it increase P uptake but also facilitates nutrient transport, enhances drought tolerance, and helps in the formation of soil aggregates by producing glomalin and other soil-binding compounds (Wahid et al., 2020). It has been reported that the beneficial effects of AMF are further enhanced when applied in combination with PSB, indicating a strong synergistic relationship between these two microbial groups (Nacoon et al., 2021).

Integrated Nutrient Management (INM)

In INM, a strategy that combines mineral fertilizers with organic and biological nutrient sources to improve soil fertility, enhance nutrient availability, and crop productivity. The most common components of INM are farmyard manure (FYM), poultry manure (PM), compost, crop residues, green manure, and biofertilizers (Krishna et al., 2025). INM has attained extensive attention as a strategy to improve PUE in the alkaline calcareous soils of Pakistan due to restricted P availability. Organic amendments release organic acids during decomposition, which enhance P availability by solubilization of calcium-bound P. Additionally, organic amendments improve soil physical, chemical, and biological properties and create favorable conditions for nutrient cycling and microbial activity (Liang et al., 2025).

Recent research in Pakistan has demonstrated the effectiveness of integrating phosphorus fertilizers with organic amendments. Naeemullah et al. (2024) reported that the integrated use of PSB and organic amendments boosts the yield of bell pepper. In addition, organic amendments increase soil organic matter content, stimulate beneficial microbial populations, improve nutrient cycling, and enhance soil structure and water-holding capacity. These improvements contribute to reduced nutrient losses and greater fertilizer efficiency, ultimately supporting sustainable crop production.

Organic Amendments and Biochar

Commonly used amendments include FYM, PM, compost, vermicompost, and biochar. The decomposition of organic materials releases carbon dioxide, organic acids, and other biochemical compounds, which dissolve calcium-bound P and increase the concentration of plant-available P. Among these organic amendments, biochar has attained great popularity as a promising soil conditioner in recent times. Biochar has the ability to improve soil structure, water-holding capacity, provide habitats for beneficial microorganisms, and reduce P sorption (Adnan et al., 2025). The integrated application of biochar and P fertilizers can significantly improve P availability, crop growth, and PUE in calcareous soils (Arif et al., 2017).

Foliar Phosphorus Fertilization

The foliar application of P is a very effective alternative method to control the P fixation issue in alkaline calcareous soils. In this method, P is directly absorbed by plant leaves, resulting in efficient P uptake, thereby increasing the PUE. We can even regulate synchronization between nutrient supply and crop demand and lower P fertilizer requirements (Rafiullah et al., 2020).

It was reported that the beneficial effects of foliar-applied P were more prominent in low soil P availability conditions (Arif et al., 2021). It is important, however, to note that foliar P application is not a complete substitute for soil-applied P, but only a partial amount can be applied because foliar application cannot satisfy the complete crop growth requirement. Therefore, combining foliar P application with appropriate soil P management can contribute to improving PUE for sustainable crop production in calcareous soils (Khan et al., 2018).

Precision Phosphorus Management

Precision agriculture techniques represent a great potential for improving P management to boost PUE. Precision P management includes variable-rate technology, remote sensing, GPS-guided fertilizer application, GIS-based nutrient mapping, and site-specific nutrient application. Such technologies offer more efficient fertilizer use and reduce excessive P use by ensuring adequate nutrient supply to crops at the right rate, place, and time (Vullaganti et al., 2025). The adoption of precision agriculture technologies is still very limited in Pakistan due to certain technical and economic constraints. Soon, as such technologies become more accessible, precision P management is expected to play an important role in sustainable nutrient management and crop production (Raza et al., 2025).

Development of Phosphorus-Efficient Crop Genotypes

Genetic improvement is a long-term strategy for enhancing PUE in crops grown on calcareous soils. By appropriate breeding for traits associated with better P acquisition and utilization by extensive root systems, greater root hair density, enhanced P uptake, efficient P remobilization, and efficient internal P utilization efficiency (Veneklaas et al., 2012). Abbas et al. (2024) revealed that different wheat genotypes have variable capacity to acquire P under alkaline calcareous soil, as some cultivars exhibit better performance in absorbing P under phosphorus-limited conditions. Such findings represent the significance of breeding programs to develop cultivars with better acquisition efficiency.

Emerging Technologies

Nano-Phosphorus Fertilizers

Nanotechnology has emerged as a promising approach for improving nutrient delivery and enhancing PUE in agricultural systems. Nano-phosphorus (nano-P) fertilizers are designed to provide controlled and targeted phosphorus release, thereby minimizing the fixation losses that commonly occur in alkaline calcareous soils. Compared with conventional P fertilizers, nano-P formulations have the potential to improve nutrient availability, enhance plant uptake, reduce application rates, and minimize environmental losses (Subramani and Balakrishnan, 2026).

Although research on nano-phosphorus fertilizers in Pakistan remains limited, recent studies suggest that their gradual nutrient-release characteristics can help maintain P availability over longer periods and improve fertilizer recovery efficiency. By reducing phosphorus immobilization and increasing nutrient-use efficiency, nano-P fertilizers may offer a viable solution to the low effectiveness of conventional P fertilization in calcareous soils. Consequently, nanotechnology is increasingly recognized as a promising future direction for sustainable phosphorus management and enhanced agricultural productivity in Pakistan (Zafar et al., 2024).

Polyphosphate Fertilizers

Polyphosphate fertilizers are considered the most advanced P source to improve the PUE in alkaline calcareous soils. In these fertilizers, chains of phosphate molecules, such as polyphosphate instead of orthophosphate like conventional P fertilizer, exist and undergo gradual hydrolysis in the soil to ensure a sustained supply of plant-available P. In this way, P mobility is enhanced, and the rapid precipitation of P is reduced, which decreases P fixation in calcareous soils (Zhang et al., 2024). Despite limited research on polyphosphate fertilizers in Pakistan, their potential to control P fixation and improve PUE suggests that they could become an important component of future P management strategies for calcareous soils.

Research Gaps

Despite the abundance of research and advances regarding improvement in PUE in alkaline calcareous soils, critical knowledge gaps still exist. Recently, studies have been done mostly for short-term and under controlled conditions. Therefore, to draw any logical conclusion, long-term field experiments may be conducted to validate the sustainability and suitability of P management practices in variable agroecological environments (Xing et al., 2025). Scarce information is available on the economic feasibility and farmer adoption of emerging new technologies, including biofertilizers, biochar, precision nutrient management, and nano-fertilizers. The microbial ecology of Pakistani calcareous soils still needs further research, which hampers the development of site-specific biological solutions for P mobilization. The lack of dedicated programs focusing on the development of P-efficient crop cultivars is another major gap.

Future Prospects

Future efforts to improve PUE in alkaline calcareous soils should focus on integrated nutrient management rather than relying solely on conventional fertilizers. Sustainable improvements will require combining biological, agronomic, genetic, and technological approaches adapted to local soil and climatic conditions. Biological strategies should emphasize the development of locally adapted PSB and AMF, particularly PSB–AMF consortia that enhance P solubilization, mobilization, and uptake. Emerging technologies such as biocharbased fertilizers, nano-P formulations, and precision nutrient management tools can further improve fertilizer recovery, reduce P fixation, and optimize nutrient application. Technologies, including remote sensing, GIS, and site-specific nutrient management, offer additional opportunities to increase efficiency while minimizing economic and environmental losses.

Future research should also prioritize climate-resilient P management and the development of P-efficient crop cultivars with enhanced P acquisition and utilization traits. Overall, a multidisciplinary approach integrating biological solutions, improved agronomic practices, advanced technologies, and crop genetics offers the greatest potential to enhance P recovery, improve soil health, reduce fertilizer dependence, and sustain agricultural productivity in Pakistan's calcareous soils.

Conclusion

Phosphorus deficiency remains a major constraint to achieving the full agronomic potential of crop production systems in Pakistan. The strong P-fixing capacity of alkaline calcareous soils not only reduces fertilizer-use efficiency but also increases production costs due to higher input requirements and low fertilizer recovery. As a result, a substantial proportion of applied P becomes unavailable to crops, limiting productivity and economic returns. Evidence from recent research indicates that PUE can be substantially improved through a range of complementary strategies, including biological interventions, integrated nutrient management, organic amendments, foliar phosphorus application, improved fertilizer placement techniques, and genetic enhancement of crop cultivars. Among these, approaches such as PSB, AMF, FYM integration, and P-efficient crop genotypes have shown considerable promise under calcareous soil conditions.

Overall, sustainable P management in Pakistan will require a multidisciplinary and systems-based approach that integrates soil health improvement, biological nutrient mobilization, precision agriculture technologies, and crop genetic enhancement. The adoption of these integrated strategies has the potential to significantly improve P recovery, enhance crop productivity, ensure economic sustainability, and reduce environmental impacts, thereby contributing to long-term food security in Pakistan.

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Annexure (A)

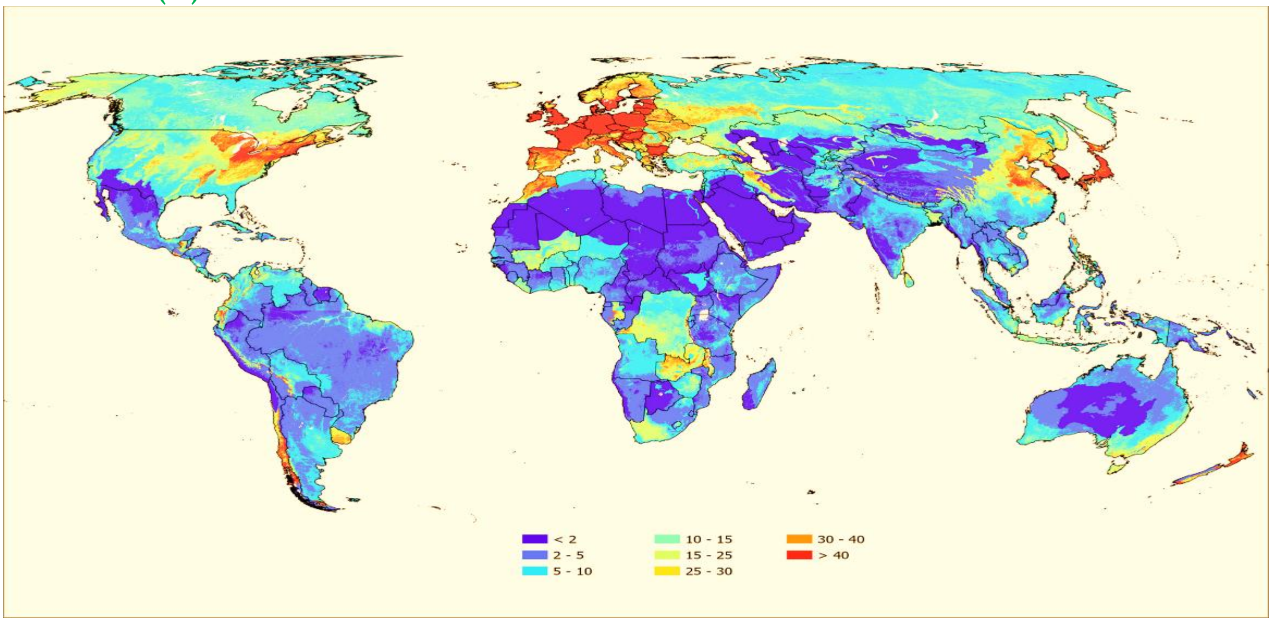

Fig. 1. Global topsoil Olsen phosphorus concentration (mg kg^{-1}). Pakistan is highlighted in a red circle (Source: McDowell et al., 2023)

Annexure (B)

Applied Phosphorus Fertilizer

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Dissolution into Soil Solution

↓

Phosphate Ions ($H_2PO_4^-$, HPO_4^{2-})

↓

High Soil pH + Excess $CaCO_3$ + Calcium Ions

↓ ↓ ↓

Dicalcium Phosphate | Hydroxyapatite | Octacalcium Phosphate

↓

Insoluble Calcium-P Forms

↓

Reduced Phosphorus Availability

↓

Low Phosphorus Uptake

↓

Reduced Growth and Crop Productivity

Fig. 2. Major phosphorus fixation pathways in Pakistan's alkaline calcareous soils

Annexure (C)

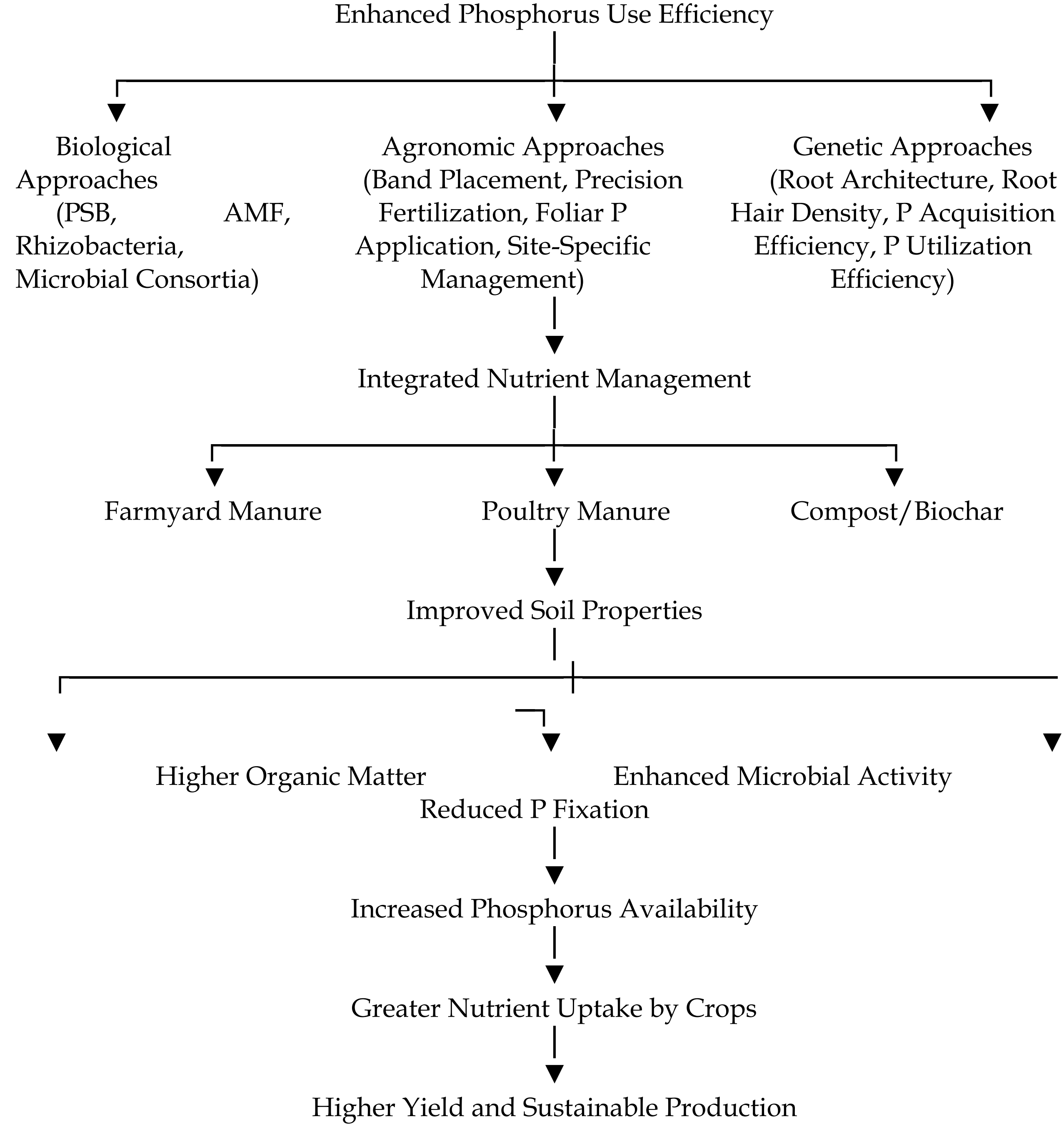

Fig. 3. Integrated Framework for Enhancing Phosphorus Use Efficiency in Pakistan's Calcareous Soils

Annexure (D)

Authors	**Crop**	**Treatment/Strategy**	**Major Findings**	**Implications for PUE**
Wahid et al., 2020	Wheat	PSB + AMF	Improved P-uptake, root colonization, and biomass production	Synergistic role of microbial inoculants in improving P availability
Hussain et al., 2021	Cereals	PSB + AMF	Increased N and P uptake, microbial	Confirmed biological mobilization of fixed P

			colonization, and root growth	
Arif et al., 2021	Wheat and Maize	Foliar P + soil P application	Enhanced P-uptake, biomass production, and PUE	Reduced P-fixation losses through supplemental foliar feeding
Adnan et al., 2022	Wheat	PSB integrated with P supplements	Improved grain yield, P availability, and PUE	Supported integrated P management strategies
Ahmad et al., 2022	Wheat	Organic and inorganic P sources	Increased P availability and crop productivity	Highlighted the benefits of integrated nutrient management
Muhammad et al., 2022	Wheat	Biozote-P under zero tillage	Improved PUE and grain yield	Demonstrated role of biofertilizers in conservation agriculture
Jamal et al., 2023	Wheat	FYM + P fertilizer	Enhanced soil quality, P availability, and wheat productivity	Confirmed synergistic effect of organic amendments
Abbas et al., 2024	Wheat	Evaluation of P-efficient genotypes	Significant variation in P acquisition and utilization efficiency among cultivars	Identified breeding potential for P-efficient wheat
Recent South Asian Studies 2024–2025	Wheat/Maize	Polyphosphate fertilizers	Improved P solubility and nutrient uptake in calcareous soils	Emerging strategy for reducing phosphorus fixation
Emerging Research 2025–2026	Multiple Crops	Nano-P fertilizers	Increased nutrient delivery efficiency and controlled nutrient release	Potential future technology for sustainable P management

Table 1. Recent Pakistani Studies on Enhancing Phosphorus Use Efficiency in Alkaline Calcareous Soils (2020–2026)

Annexure (E)

Strategy	Primary Mechanism	Effect on Soil Phosphorus	Effect on Crop Performance
Phosphate-Solubilizing Bacteria (PSB)	Organic acid secretion, proton release, and chelation	Solubilizes calcium-bound phosphorus	Improves phosphorus uptake and yield
Arbuscular Mycorrhizal Fungi (AMF)	Hyphal extension beyond depletion zones	Enhances phosphorus acquisition from soil	Increases nutrient uptake and stress tolerance
Farmyard Manure (FYM)	Organic acid production during decomposition	Reduces phosphorus fixation	Improves nutrient availability and soil health
Poultry Manure	Mineralization of organic phosphorus	Increases the available phosphorus pool	Enhances crop growth and biomass
Compost	Nutrient release and microbial stimulation	Improves phosphorus cycling	Increases productivity
Biochar	Reduced phosphorus sorption and improved microbial habitat	Enhances phosphorus retention and availability	Improves fertilizer efficiency
Foliar Phosphorus Application	Direct nutrient absorption through leaves	Bypasses soil fixation processes	Rapid correction of phosphorus deficiency

Band Placement of Fertilizer	Localized nutrient concentration	Minimizes phosphorus-calcium interactions	Increases fertilizer recovery efficiency
Precision Nutrient Management	Site-specific phosphorus application	Optimizes nutrient distribution	Reduces fertilizer losses
Nano-Phosphorus Fertilizers	Controlled nutrient release	Enhances phosphorus availability over time	Improves nutrient-use efficiency
Polyphosphate Fertilizers	Greater mobility and gradual hydrolysis	Improves phosphorus solubility	Enhances nutrient uptake
Phosphorus-Efficient Genotypes	Enhanced root architecture and nutrient utilization	Greater phosphorus acquisition efficiency	Higher yield under phosphorus stress

Table 2. Mechanisms Involved in Enhancing Phosphorus Use Efficiency in Alkaline Calcareous Soils