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Unlocking Phosphorus Potential in Indian Soils for Sustainable Crop Production

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Phosphorus (P) is one of the three primary macronutrients essential for plant growth, alongside nitrogen and potassium. It is essential for a number of physiological and biochemical functions, including signal transduction, photosynthesis, nucleic acid synthesis, energy transfer through adenosine triphosphate (ATP), and enzyme control (*Havlin et al., 2014*). Due to its strong fixation with soil minerals and low solubility, phosphorus—the eleventh most prevalent element in the Earth's crust—is frequently limited in its availability in soils (*Lindsay, 1979*). As a result, it becomes one of the nutrients that limits crop yields the most in many cropping systems, especially in tropical and subtropical areas like India.

Phosphorus requires external addition because it does not have a similar replenishment pathway to nitrogen, which may be restored biologically through atmospheric fixation. After being added to the soil, phosphorus fixes itself in forms that plants cannot use by interacting with calcium compounds in alkaline soils and aluminum and iron oxides in acidic soils (*Sanyal and De Datta, 1991*). Therefore, only a small portion of the total soil phosphorus—usually less than 0.1%—is always easily available to crops (*Richardson and Simpson, 2011*).

One of the most common concerns in India is phosphorus deficiency. Approximately 42% of India's farmed soils are classified as having low levels of accessible phosphorus (*Sharma et al., 2021*), especially in areas like the Deccan Plateau, the Indo-Gangetic Plains, and the red and lateritic soils of eastern India. Intensive farming, dwindling organic matter, and uneven fertilizer use exacerbate the issue by lowering phosphorus availability and jeopardizing soil health (*Kumar et al., 2018*).

The fact that phosphate rock, the raw material needed to make phosphorus fertilizers, is limited further complicates the problem. Concerns of long-term sustainability are raised by the unequal distribution and non-renewability of global reserves (Cordell et al., 2009). Furthermore, excessive usage of phosphorus fertilizers can lead to environmental problems including water body eutrophication from nutrient runoff (*Withers et al., 2015*). The significance of biological and organic processes in phosphorus mobilization has been brought to light by initiatives to improve phosphorus use efficiency (PUE). By producing phosphatase, exuding organic acids, and enhancing root-soil interaction, phosphate-solubilizing bacteria (PSB) and arbuscular mycorrhizal fungus (AMF) increase the availability of phosphorus (*Richardson and Simpson, 2011*). By enhancing soil structure and boosting microbial activity, organic amendments like compost and green manure also aid in the cycling of phosphorus (*Singh et al., 2019*).

According to (*Patel et al. 2020*), new technologies are being developed to solve phosphorus inefficiency, including slow-release formulations, site-specific nutrient management tools, and nano-phosphorus fertilizers. Concurrently, efforts to improve phosphorus uptake in low-P environments through plant breeding that focuses on root characteristics such as architecture, exudation, and rhizosphere changes show promise (*Lynch, 2011*). This article offers a thorough examination of the dynamics of phosphorus in Indian soils, emphasizing its availability, the ways in which it is fixed in various soil types, and methods for increasing the effectiveness of phosphorus use. For India to develop robust and fruitful farming systems, a better knowledge of the relationships between soil, plants, and phosphorus is necessary.

Importance of Phosphorus in Plant and Soil

Phosphorus (P) is an essential macronutrient that plays a vital role in multiple physiological and biochemical processes within plant systems. It is required in relatively large amounts and is particularly important during early growth stages and reproductive development.

Key Functions of Phosphorus in Plants:

- Energy Transfer and Metabolism: Adenosine triphosphate (ATP) and adenosine diphosphate (ADP), which are molecules in charge of energy storage and transfer in plant cells, are structurally composed of phosphorus. These are essential for respiration, photosynthesis, and all other metabolic processes.
- Genetic and Cellular Function: Protein synthesis, cell division, and genetic transmission all depend on nucleic acids (DNA and RNA), of which phosphorus is a crucial component.
- Root Development: Especially during the seedling stage, a sufficient supply of phosphorus encourages robust root growth, which improves nutrient and water intake.
- Flowering and Seed Production: The growth of flowers, fruits, and seeds depends on phosphorus. It has a direct impact on grain maturity and quality, making it an essential nutrient for successful reproduction.
- Stress Resistance: Plants that are phosphorus-rich are better able to withstand biotic and abiotic challenges including cold, disease, and drought. Phosphorus-rich plants frequently respond better to immunological stimuli and are more resilient in adverse environments.

➢ **Symptoms of Phosphorus Deficiency in Plants:**

- **Poor development of the root system**
- **Slow growth and delayed maturity**
- **Reddish or purpling of older leaves as a result of anthocyanin buildup**
- Low yield and subpar quality of grains, seeds, or fruits

Importance of Phosphorus in Soil Systems

Phosphorus dynamics in the soil are complex, involving various chemical, physical, and biological processes that regulate its availability to plants. Although total phosphorus in soil may be high, only a small portion exists in a soluble form that is readily available to crops.

➢ **Roles and Importance of Phosphorus in Soil:**

- **Soil Fertility Indicator:** Plant-available phosphorus is a key indicator of soil fertility. Soils deficient in available P limit crop productivity and long-term agricultural sustainability.
- **Microbial Activity and Soil Life:** Soil microbes require phosphorus for energy and growth. Microorganisms involved in organic matter decomposition, nitrogen fixation, and phosphorus mineralization depend on adequate P levels for optimal functioning.
- **Nutrient Cycling:** Phosphorus is an integral part of the nutrient cycle in soil ecosystems. It undergoes processes like mineralization, immobilization, adsorption-desorption, and precipitation-dissolution, which regulate its movement between organic and inorganic pools.
- **Soil-Plant Interactions:** Phosphorus availability affects plant-microbe interactions in the rhizosphere. Phosphate-solubilizing bacteria (PSB) and arbuscular mycorrhizal fungi (AMF) facilitate phosphorus uptake, improve nutrient-use efficiency, and contribute to soil health.

- **Soil Structure and Organic Matter Dynamics:** Organic phosphorus compounds contribute to soil structure by forming stable aggregates. This enhances water retention, aeration, and root penetration.

Soil Status of Available Phosphorus in Indian Soils

The availability of phosphorus (P) in Indian soils is a significant challenge for sustainable agriculture because P-deficient soils are found in many different agro-ecological zones. Phosphorus is the second most limiting nutrient after nitrogen, however because of its strong fixation tendency and limited solubility, it behaves much more complexly in soil. Though it is mostly found in forms that plants cannot use, phosphorus is frequently present in sufficient overall amounts in Indian soils. Indian soils' high phosphorus fixation capacity is mostly caused by their mineral makeup, particularly the presence of calcium (Ca), aluminum (Al), and free iron (Fe) oxides (*Datta et al., 2020; Singh et al., 2019*).

General Phosphorus Availability Status in India

The Indian Council of Agricultural Research (ICAR) and several State Agricultural Universities (SAUs) have carried out soil surveys around the country, and the results indicate that:

- About **42–45%** of cultivated soils in India are **low in available phosphorus** (less than 10 kg P_2O_5/ha),
- Around **40–45%** are **medium** (10–25 kg P_2O_5/ha),
- Only about **10–15%** are **high** in available phosphorus (>25 kg P_2O_5/ha) (ICAR-IISS, 2018; Tiwari et al., 2019).

In rainfed locations with low levels of organic matter and fertilizer use, the shortage is particularly noticeable. In heavily irrigated areas, the shortage has been made worse by ongoing agriculture without sufficient P replenishment**.**

Soil-Type-Wise Phosphorus Status in India

Soil Type	Geographic Region	Phosphorus Status
Alluvial Soils	Indo-Gangetic Plains (Punjab, UP, Bihar)	Low to medium; moderate P fixation due to Ca and Fe compounds (*Sharma et al., 2021*).
Black Soils (Regur)	Maharashtra, MP, Gujarat, Karnataka	Low to medium; high P fixation due to $CaCO_3$ and clay minerals (*Rattan et al., 2014*).
Red Soils	Tamil Nadu, Odisha, AP, Karnataka	Low; high Fe/Al oxide content leads to strong fixation (*Singh et al., 2019*).
Lateritic Soils	Kerala, Bengal, Western Ghats	Very low in P due to high weathering and strong fixation (*Datta et al., 2020*).
Desert Soils	Rajasthan, Gujarat	Variable, often low due to sandy texture and poor nutrient retention (*ICAR-IISS, 2018*).
Mountain Soils	Himalayas, NE States	Low due to leaching and acidic pH (*Munda et al., 2020*).
Peaty/Organic Soils	Kerala, Bengal, Assam	Medium to high organic P, but low mineral P availability (*Tiwari et al., 2019*).
Coastal Saline/Alkali Soils	Odisha, WB, Gujarat	Low to medium; P availability limited by high pH and salinity (*ICAR-IISS, 2018*).

Regional Observations and State-Level Trends

- **Punjab & Haryana:** Emerging P deficiency despite high fertilizer use; declining crop response due to imbalanced N:P ratio (*Sharma et al., 2021*).
- **Madhya Pradesh & Maharashtra:** Red and black soils are P-deficient due to fixation and rainfed conditions.
- **UP & Bihar:** Alluvial soils show medium P, but intensive cropping is reducing reserves.
- **South India:** Lateritic and red soils are severely P-deficient.

- **NE States & Hill Areas:** Leaching and low organic matter lead to widespread P deficiency.

Causes for Low Phosphorus Availability in Indian Soils

- **High Fixation Capacity:** Due to Al, Fe, and Ca compounds binding P into insoluble forms.
- **Low Organic Carbon:** Poor organic matter reduces mineralization and microbial solubilization.
- **Imbalanced Fertilizer Use:** Excess N and minimal P application disturbs nutrient balance.
- **Continuous Cropping:** Nutrient mining without replenishment reduces soil fertility (*Rattan et al., 2014*).
- **Erosion and Leaching:** Especially in high rainfall and sloping areas.

Recent Trends and Concerns

- **Nutrient Mining:** ICAR reports that Indian soils annually lose ~3.5 million tonnes of P through crop removal (*ICAR-IISS, 2018*).
- **Declining Response:** Even in medium to high P soils, crop yield response is falling due to fixation and declining soil health (*Tiwari et al., 2019*).
- **Environmental Impacts:** Localized over-application (e.g., in Punjab) leads to eutrophication risks in water bodies.

Mechanisms of Phosphorus Fixation in Different Types of Soils

Phosphorus (P) fixation is the process that transforms soluble phosphate ions into forms that are less accessible to plants and sparingly soluble. This happens as a result of immobilization, precipitation, or adsorption, depending on the physical and chemical characteristics of the soil. Because different soil types differ in terms of pH, clay mineralogy, oxide concentration, and organic matter, the degree and kind of fixation varies greatly (*Lindsay, 1979; Rattan et al., 2014*).

Table-1: Mechanisms of Phosphorus Fixation in Indian Soils with References

Soil Type	Dominant Fixation Mechanism	Key Fixing Agents	pH Range	Geographical Regions	References
Acidic (Red, Lateritic)	Precipitation with Fe^{3+} and Al^{3+} as insoluble P	Iron and aluminum oxides	< 5.5	Odisha, Jharkhand, West Bengal, Kerala	*Sanyal & De Datta (1991); Sharma et al. (2021)*
Alluvial (Neutral)	Adsorption and slow precipitation with Fe/Al/Ca	Ca^{2+}, Fe^{3+}, Al^{3+}	6.5–7.5	Indo-Gangetic plains (UP, Bihar, Punjab)	*Datta et al. (1989); FAI (2011)*
Calcareous	Formation of dicalcium/tricalcium phosphate	Calcium carbonate	> 7.5	Gujarat, Rajasthan, Western UP	*Rajan et al. (2005); Tandon (2009)*
Black Cotton Soils	Fixation with Ca^{2+} and some Fe/Al under sub-alkaline	Smectite clay, Ca^{2}	7.0–8.0	Maharashtra, MP, Karnataka	*Pathak et al. (2010); FAO (2005)*
Organic (Peaty)	Immobilization by microbes, some complexing of Fe/Al	Organic matter	4.5–6.5	Kerala, Coastal WB, NE India	*Sanyal & De Datta (1991); Singh & Singh (2004)*

Factors Influencing the Availability of Phosphorus in Soil

The amount of phosphorus (P) in the soil is a crucial factor in determining plant production since it is essential for energy transmission, photosynthesis, root growth, and blooming.

Phosphorus is found in most soils in sufficient proportions, but because of a number of interrelated chemical, physical, and biological variables, only a small portion of it is available for plant uptake.

Table-2: Factors Influencing Phosphorus Availability in Soil

Factor	Mechanism Affecting P Availability	Effect on P	References
Soil pH	Influences P solubility via Fe, Al, and Ca reactions	High fixation at extremes	*Sanyal & De Datta (1991); Tandon (2009)*
Soil Texture & Clay Type	Provides adsorption sites; type of clay affects retention	High in clayey soils	*Singh & Singh (2004); Sharma et al. (2021)*
Organic Matter	Chelates cations; releases acids; stimulates microbes	Increases availability	*Singh & Singh (2004); Sharma et al. (2021)*
Microbial Activity	Mineralizes organic P; solubilizes inorganic P	Enhances P solubility	*Rodriguez & Fraga (1999); Sharma et al. (2020)*
Soil Moisture & Aeration	Affects P diffusion and microbial function	Moderate to strong effect	*FAO (2005); Tandon (2009)*
Fertilizer Management	Placement and type affect fixation and uptake	Can reduce losses	*FAI (2011); Rajan et al. (2005)*
Cation Composition	Precipitates P as insoluble forms (Fe-P, Al-P, Ca-P)	Reduces P availability	*Sanyal & De Datta (1991); Pathak et al. (2010)*
Root Traits & Exudates	Increase rhizosphere solubilization and uptake area	Improves P uptake efficiency	*Hinsinger (2001); Richardson et al. (2009)*

Strategies for Management to Increase Phosphorus Availability

Most soils contain phosphorus, but a significant amount of it is fixed in forms that are not available. It is essential to implement management techniques that reduce fixation, increase solubilization, and promote absorption in order to maximize crop yield and phosphorus use efficiency (PUE).

Balanced Fertilizer Application

- Apply phosphorus based on soil test recommendations.
- Avoid excess or blanket applications.
- Use integrated nutrient management (INM) with NPK and organic sources.

Use of Phosphate-Solubilizing Microorganisms (PSMs)

- Include PSBs (e.g., *Bacillus*, *Pseudomonas*) or mycorrhizal fungi (AMF).
- These microbes secrete organic acids (e.g., citric, oxalic) that solubilize fixed P.
- Enhance root absorption via symbiotic relationships.

Organic Matter and Compost Application

- Organic materials (FYM, green manure, compost) release organic acids and chelate Fe/Al/Ca, releasing phosphorus.
- Vermicompost also enhances microbial activity and improves phosphorus mobility.

pH Management

- Lime acidic soils ($pH < 5.5$) to reduce Al and Fe fixation.
- Use acid-forming fertilizers (e.g., ammonium sulfate) in alkaline soils to lower rhizosphere pH.

Placement Techniques

- Band placement or drilling reduces phosphorus fixation by limiting contact with soil particles.
- Foliar sprays of phosphorus are effective in micronutrient-deficient areas.

Use of Rock Phosphate and Its Modified Forms

- In acidic soils, rock phosphate (RP) is more soluble and can be used effectively.
- Enhanced RP (e.g., partially acidulated rock phosphate or enriched composts) improves P availability.

Crop Selection and Rotation

- Use P-efficient crop varieties with better root traits (e.g., longer root hairs, high exudate production).
- Include legumes in rotation to improve microbial diversity and phosphorus cycling.

Use of Nano and Slow-Release Phosphorus Fertilizers

- Nano P fertilizers increase surface area and solubility.
- Slow-release formulations reduce fixation and extend phosphorus availability during crop growth.

Rhizosphere Engineering

- Promote root exudation and interaction with beneficial microbes.
- Use bio-stimulants and organic inputs to enhance rhizosphere functions.

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