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A REVIEW OF AVAILABLE PHOSPHOROUS FERTILIZER IMPACT ON GROWTH AND DEVELOPMENT OF WHEAT

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ABSTRACT

One of the world's most significant cereal crops is wheat (*Triticum aestivum*). Inadequate productivity and output of wheat are known to be primarily impeded by inadequate soil fertility. One of the world's most significant cereal crops is wheat (*Triticum aestivum*.). Inadequate soil fertility is known to be the main cause of wheat's low productivity and output. Phosphorus (P) is one of the major elements required for the production of wheat. It is crucial to a number of physiological processes that take place in a growing and mature plant. Depending on the pH of the soil, it can exist as an anion in the soil solution as either di- or mono-hydrogen phosphate ($H_2PO_4^-$). Since many soils lack enough phosphorus to support crop growth, phosphorus fertilization is a crucial input in crop production. Phosphorus is necessary for plant development, starch and sugar uptake, photosynthesis, nucleus formation, and cell division. Increased root development indicates that there is a sufficient amount of accessible P in the soil, allowing roots to sift through more soil in search of moisture and nutrients. P deficits cause plants to develop more slowly. The main ways that phosphorus is removed from agricultural fields are by attachments to the sediment that erodes away from the field, dissolution in surface water runoff, or dissolution in locates that are then transferred through the soil profile. In order to provide the necessary nutrients to the plant, nutrient management strategies must balance crop demand and soil supply, promote the growth of P-efficient crops, and increase the efficiency of P recycling in the future.

***Keywords*: Phosphorus, Nutrient, Soil, Production and Wheat.**

Introduction

Wheat is the most extensively cultivated cereal grain around the globe and holds a crucial place in agriculture. It is a principal nutriment for 36% of the world's populace and is propagated in 70 % of the world's cultivated regions Riaz *et al.* (2021). Internationally, wheat supplies approximately 55% of the carbohydrates and 21% of food calories consumed worldwide. Numerous physiological activities that take place inside a growing and mature plant depend on phosphorus. It participates in the plant's enzymatic processes. Since phosphorus is a component of nucleoproteins, which are involved in the processes of cell reproduction, it is necessary for cell division. It is also a part of a chemical that is essential for the synthesis and breakdown of carbohydrates. Phosphorus is crucial for the development of seeds, fruits, and crops. It accelerates fruit ripening and mitigates the effects of excessive nitrogen fertilizer application to the soil. By avoiding lodging, it contributes to strengthening the plant's skeletal structure. It may enhance the plant's resilience to diseases and also influence the grain's quality.

Phosphorus, categorized as a significant element in plants, is a part of many proteins and enzymes and is involved in multiple energy transfer mechanisms.

Depending on the pH of the soil, phosphorus can exist as an anion in the soil solution, either as mono-hydrogen phosphate (HPO_4^{2-}) or di-hydrogen phosphate ($H_2PO_4^-$). As the second nutrient listed by concentration in the form of phosphorus pentoxide (P_2O_5), it is classified as a fertilizer element. Fertilization with phosphorus is crucial for agricultural development since many soils lack sufficient phosphorus to support productive crop growth.

Phosphorus must be supplied to crops in adequate amounts early in the growing season to maximize nutrition. Since phosphorus is essential to almost every energy-consuming function in plants, it is required from the very beginning of crop growth. Phosphorus stress early in the growing season reduces crop productivity more significantly than phosphorus limitations later in the season. This review paper aims to examine the effect of phosphorus fertilizer on wheat growth and development.

Phosphorous availability to wheat crop

Phosphorus exists in soils in roughly equal quantities between its organic and inorganic forms, both of which are vital contributors to plant nutrition. Within the soil solution, phosphorus is present in two main anionic forms: di-hydrogen phosphate ($H_2PO_4^-$) and mono-hydrogen phosphate (HPO_4^{2-}). The soil water's pH has a crucial influence on the predominance and relative concentrations of these two forms, significantly affecting phosphorus's availability to plants.

Among inorganic sources of phosphorus, phosphates of aluminum (Al), iron (Fe), and calcium (Ca) serve as primary contributors. The proportions of these types vary depending on the pH of the soil water, which determines the chemical interactions and availability of phosphorus. For example, in acidic soils, aluminum and iron phosphates dominate, while calcium phosphates are more common in alkaline soils.

In addition to inorganic sources, the decomposition of agricultural residues, such as crop remnants, and the activity of soil microbes release phosphorus into the soil solution. This process can provide a significant source of plant-available phosphorus, supplementing inorganic phosphorus pools.

The availability of phosphorus to plants is intricately tied to the soil water's pH levels. In acidic environments, phosphorus may become "fixed" or bound to aluminum and iron, rendering it less available for plant uptake. Conversely, in alkaline soils, phosphorus can form calcium-phosphate compounds that also reduce its solubility. As such, maintaining an optimal soil pH is critical to ensuring adequate phosphorus nutrition for crops.

Phosphorus availability is a key factor in overall soil fertility and directly impacts crop productivity and health.

Roles of Phosphorous in wheat growth and development

(a) Energy transmission and storage:

Phosphorus is a vital nutrient for plants, playing a central role in numerous physiological and biochemical processes. It is indispensable for plant development, starch and sugar uptake, photosynthesis, nucleus formation, and cell division. In addition, phosphorus molecules are integral to energy storage and transfer within plants. Phosphate compounds capture energy produced during photosynthesis and carbohydrate metabolism, storing it for use in later stages of growth, reproduction, and overall plant development.

One of the remarkable features of phosphorus is its mobility within plants. It can be readily translocated from older tissues to younger, actively growing regions such as roots, stems, and leaves. This ensures that phosphorus supports the most critical phases of plant growth. Adequate phosphorus levels enable rapid development and early maturation, which is particularly important in areas prone to frost. Furthermore, phosphorus significantly enhances the quality of vegetative crop growth and strengthens overall plant health.

(b) Phosphorous for wheat growth

Phosphorus is indispensable for wheat growth, as it plays a central role in respiration, photosynthesis, and the transmission of cellular energy. Additionally, phosphorus is a structural component of various coenzymes, phospho-proteins, phospholipids, and the nucleic acids found in genes and chromosomes Ozanne (1980).

A sufficient supply of phosphorus early in the wheat crop establishment is crucial for ensuring optimal growth and development. Early-season phosphorus deficiencies can have a profound impact on crop development, potentially causing limitations from which the plant may not fully recover even if phosphorus levels are later increased to appropriate amounts.

Phosphorus plays a pivotal role in an extensive range of biological and physiological processes within plants. It is involved in energy production, nucleic acid synthesis, photosynthesis, glycolysis, respiration, membrane construction and stability, signalling, redox reactions, enzyme activation and inactivation, carbohydrate metabolism, and nitrogen fixation. This element is particularly concentrated in actively developing tissues of young, growing plants.

By the time plants reach approximately 25% of their total dry weight, they may have acquired up to 75% of their total phosphorus needs. This underscores the critical importance of phosphorus during the early stages of plant growth. In the case of wheat, sufficient phosphorus availability in the initial phases of development is crucial for supporting optimal growth, given its role in numerous biochemical activities.

Phosphorus is essential for plant development, including starch and sugar uptake, photosynthesis, nucleus formation, and cell division. Phosphorus molecules facilitate the movement and storage of energy within plants. Energy derived from photosynthesis and carbohydrate metabolism is stored in phosphate compounds, ensuring its availability for subsequent growth and reproduction stages.

One of phosphorus's key attributes is its mobility within plants. It is readily translocated between older and younger tissues as the plant divides cells and develops new roots, stems, and leaves. This efficient distribution ensures that phosphorus fulfils the demands of actively growing regions.

Increased root development indicates that a sufficient amount of accessible phosphorus (P) is present in the soil, enabling roots to explore a larger volume of soil for moisture and nutrients. On a dry weight basis, phosphorus is generally found in most plants in concentrations ranging from 0.1% to 0.4%. Phosphorus deficiencies slow down overall plant growth and delay crop maturity. Phosphorus treatments have demonstrated significant yield improvements in wheat, which is attributed to the relatively low phosphorus content in many soils.

Soil phosphorus availability directly influences the morphological and physiological traits of roots, which are crucial for efficient phosphorus absorption. This makes phosphorus essential for the early growth and development of wheat Hajabbasi and Schumacher (1994). Sharif Zia *et al.* (1988) observed that varying phosphorus application rates had a significant impact on wheat dry matter yield, phosphorus tissue concentration, and phosphorus absorption. They identified the hazardous and critical limits for phosphorus in wheat development as above 3.6 mg g^{-1} (0.36%) dry matter and below 1.4 mg g^{-1} (0.14%) dry matter, respectively.

(c) Forms of P taken up by the wheat

Phosphorus applied as fertilizer can exist in various forms, depending on the chemical composition of the fertilizer. These forms include orthophosphate anion ($P3O_4^-$), diphosphate anion ($H_2PO_4^-$), or monophosphate anion (HPO_4^{2-}). For phosphorus to be absorbed by plant roots, a complex interplay of soil chemistry processes is required.

When a highly soluble form of phosphorus, such as phosphoric acid (H_3PO_4), is applied to the soil, the orthophosphate anion (PO_4^{3-}) rapidly interacts with the soil matrix. This interaction results in the precipitation of phosphorus with elements like calcium (Ca), iron (Fe), and aluminum (Al), reducing its immediate availability. The remaining soluble phosphorus in the soil solution exists in the form of either diphosphate ($H_2PO_4^-$) or monophosphate (HPO_4^{2-}), with the prevailing form influenced by the soil's pH.

Phosphorus primarily moves within the soil through diffusion. The specific type of phosphorus present in a nutrient solution also depends on the pH level. Acidic solutions contain di-hydrogen phosphate ($H_2PO_4^-$) and mono-hydrogen phosphate (HPO_4^{2-}), whereas alkaline solutions (pH > 7.0) favour the presence of triphosphate (PO_4^{3-}).

Due to the extremely low concentrations of phosphorus ions in soil solutions, typically in the micromolar range, plants rely on high-affinity active transport mechanisms for phosphorus absorption. This process involves a steep chemical potential gradient across the plasma membranes of root epidermal and cortical cells.

(d) Deficiency of P in wheat

Phosphorus deprivation can significantly impact plant physiological processes, particularly respiration and photosynthesis. When respiration is more severely affected than photosynthesis, carbohydrates accumulate in plant tissues, causing the leaves to turn dark green Glass *et al.* (1980). Prolonged phosphorus deficiencies may also lead to colour changes, with plants transitioning from dark green to purple Hoppo *et al.* (2000). These deficits disrupt the synthesis of proteins and nucleic acids, resulting in the accumulation of soluble nitrogen molecules within tissues. Consequently, cell development slows down and may even come to a halt.

Typical signs of phosphorus deficiency include reduced plant height, delayed leaf emergence, weak and slow growth, and stunted plants. Older leaves may exhibit dark green coloration with purple pigmentation, as phosphorus is relatively mobile within plants and deficiency symptoms often appear first in older tissues. In response to low phosphorus levels, plants allocate more carbon to root systems, which stimulates increased root growth, the formation of more lateral roots, deeper exploration of surface soil, and the production of longer, more abundant root hairs Liao *et al.* (2001); Lynch *et al.* (2001); Williamson *et al.* (2001).

The duration and severity of developmental stunting caused by phosphorus deficiency depend on the plant's phosphorus reserves. Increased root development is a clear indicator of accessible phosphorus in the soil, enabling roots to search more effectively for moisture and nutrients. Even a modest phosphorus shortage can hinder crop development significantly, although such deficiencies may be difficult to detect visually. Severe phosphorus deficiencies, however, manifest distinct symptoms such as browning, purpling, or stunting. These symptoms generally begin at the base of the stem and lower leaves, progressing upward, especially in grain crops. Initially, the symptoms appear at the leaf tips and then extend toward the roots. In severe cases, leaf tips eventually die off.

Diagnosing phosphorus deficiencies visually can be challenging; soil testing and plant tissue analysis are essential for accurate confirmation. Young plants often show more pronounced symptoms due to their rapid growth, which places higher demands on the limited phosphorus supply. Unfortunately, phosphorus deficiencies are rarely fully outgrown by crops, often resulting in lingering symptoms that delay maturity and reduce overall productivity.

Phosphorous fixation capacity of soils

The process known as "P fixation" reduces the amount of phosphorus (P) available to plants by transforming easily soluble forms of P into sparingly soluble ones through reactions with inorganic and organic soil components, among other mechanisms. Generally, "fixation" refers to the conversion of soluble soil phosphate into insoluble forms. This process occurs whenever an event decreases the concentration of orthophosphate ions in a solution in contact with the soil.

The primary cause of phosphorus fixation in soils is the presence of hydrated oxides, particularly complexes of iron (Fe) and aluminum (Al). Several factors influence the extent of phosphorus fixation, including the phosphate concentration in the solution, soil pH, temperature, reaction time, the ratio of soil sample weight to solution volume, and the physico-chemical properties of the soil.

It is well-established that soils can fix phosphorus, though researchers occasionally express differing views on the specific mechanisms. P fixation is thought to occur through three distinct processes, which may overlap:

1. At pH values between 2 and 5, the slow dissolution of Fe_3O_4 and aluminum oxides occurs, followed by their reprecipitation as phosphates.
2. At pH values between 4.5 and 7.5, phosphorus is fixed on the surfaces of clay particles.
3. At pH values between 6 and 10, divalent cations precipitate phosphorus.

In different soil types, multiple mechanisms may work together to regulate phosphorus fixation, with variations depending on soil composition and environmental factors.

(i) Phosphorous content of soils

Phosphorus availability to plants can be assessed by evaluating both the phosphate concentration in the soil solution and the soil's capacity to maintain this concentration over time. Even at very high concentrations, phosphorus in the soil solution ranges from only 0.3 to 3.0 kg ha^{-1} (0.3–3.0 lb ac^{-1}). Rapidly growing crops typically absorb around 1 kg ha^{-1} (1.0 lb ac^{-1}) of phosphorus daily, making it essential for the "labile" phosphorus pool in the soil to replenish the soil solution's phosphorus supply.

The labile phosphorus pool consists of phosphorus that is less immediately accessible to plants but can undergo chemical or biological transformations to replenish available phosphorus. It is important to note that annual applications of commercial fertilizers and regular animal manure use have gradually elevated phosphorus levels in certain soils. Consequently, wheat planted in soils with higher phosphorus levels may exhibit a less pronounced response to phosphorus fertilizer application compared to soils with lower phosphorus levels.

The rate and method of phosphorus fertilizer application can also influence wheat's ability to absorb phosphorus. The accessibility of phosphorus in the soil directly determines wheat's response to applied phosphorus fertilizers. Due to phosphorus's low mobility in soil, soil test values typically rely on sampling depths of 0 to 15 cm (0–6 inches), where the highest phosphorus concentration is found in the surface soil.

Phosphorus is temporarily bound within organic components of microorganisms but is released back into the soil as these microorganisms die and decompose. Through mineralization the process of converting organic phosphorus into inorganic phosphorus plants can absorb phosphorus from the soil. In more acidic soils (pH < 6.0), elevated iron and aluminum levels may either fix or remove phosphorus from the soil solution. At soil pH levels below 5.0, this process substantially reduces the availability of inorganic phosphorus to plants.

(ii) Sources of phosphorous

P is available in both liquid and granular form from the fertiliser sources indicated in Table 1: H_2PO^{-4} or HPO_4^{-2}. The majority of crops employ these two types of P, which are together known as orthophosphate. The choice of P fertiliser source is influenced by local fertiliser availability, farmer desire or equipment availability, as well as economics. Plants are not affected by the source of P.

Table 9 : Sources of Phosphorous

Source	Formula	Form % Available P_2O_5	
		Citrate soluble	**Water soluble**
Superphosphate	$Ca(H_2PO_4)$ 2	Solid	90
Concentrated superphosphate	$Ca(H_2PO_4)2$	Solid	92-98
Mono-ammonium phosphate	$NH_4H_2PO_4$	Solid	100
Di-ammonium phosphate	(NH_4) $2HPO_4$	Solid	100
Ammonium polyphosphate	(NH_4) 2 HP_2 $O_7 \times H_2O$	Solid	100
Phosphoric acid	H_3PO_4	Liquid	100
Rock-phosphate, Flour-and chloro-apatite	$3Ca_4(PO_4)$ $2CaF_2$	Solid	-
Basic slag	$5CaO\text{-}P_2O_5SiO_2$	Solid	-
Bone meal	-	Solid	-
Manure or compost	-	Solid	-

Movement of Phosphorous in the soils

The primary method by which phosphate (H_2PO^{-4} and HPO_4^{-2}) anions come into contact with the root surface is by diffusion in the soil solution. A large number of root hairs and root interception will greatly boost the possibility of P absorption (Fig. 1). A P shortage may result from reduced P absorption caused by cool soil temperatures and low soil moisture levels.

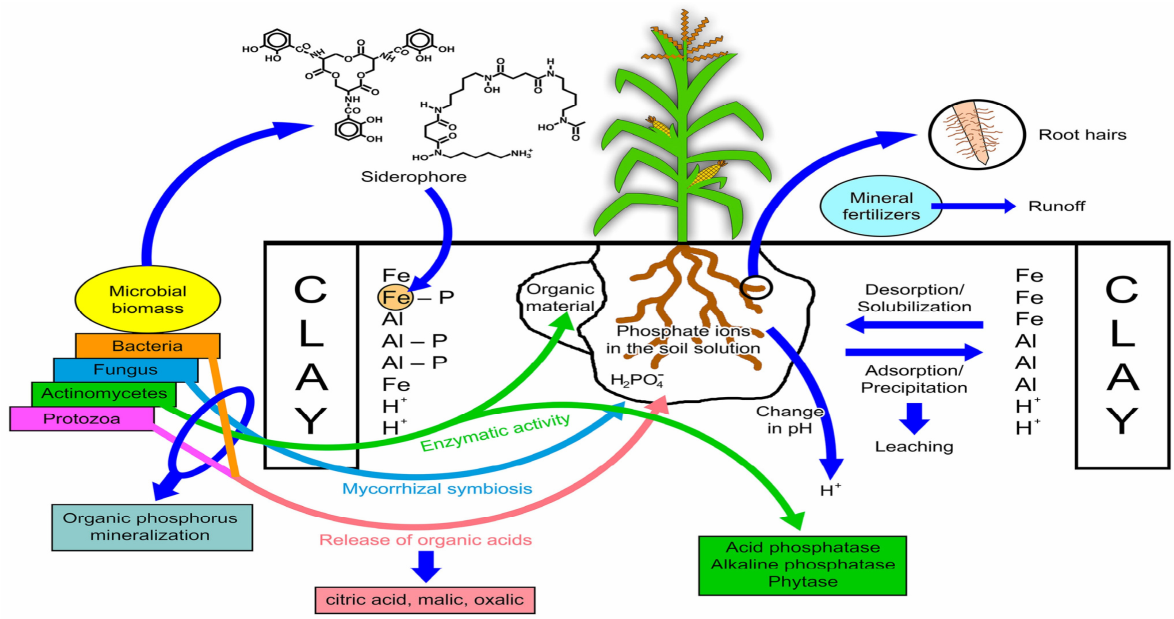

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Fig. 1 : Movement of Phosphorous in the soils

Phosphorus dynamics in the soils

Soil phosphorus (P) exists in two major forms: inorganic P (Pi) and organic P (Po), each exhibiting distinct behaviours and fates in soil ecosystems Hansen *et al.* (2004); Turner *et al.* (2002). Pi, which comprises 35% to 70% of total soil phosphorus according to Harrison's estimations Harrison *et al.* (1987) plays a direct role in plant nutrition. While the direct application of phosphate rocks, such as apatite, has been shown to be effective in acidic soils, the release of available P from primary P minerals, such as apatite, Strangite, and variscite, is generally too slow to meet the immediate demands of crops, shows in Fig. 2. This limitation highlights the challenges associated with phosphorus bioavailability.

Secondary P minerals, including calcium (Ca), iron (Fe), and aluminum (Al) phosphates, exhibit dissolution rates that vary based on mineral particle size and soil pH Pierzynski and McDowell (2005); Oelkers and Valsami-Jones (2008). In soils with increasing pH values, the solubility of calcium phosphates declines, except at pH levels above 8, while the solubility of iron and aluminum phosphates increases Hinsinger (2001). Desorption processes further contribute to phosphorus dynamics, as P adsorbed on clays and Fe/Al oxides can be released into the soil solution. These transformations enable phosphorus to move between pools that range from stable, less accessible forms to plant-available pools like labile P and solution P.

Soil organic phosphorus (Po) also contributes to the phosphorus cycle and encompasses stabilized forms such as inositol phosphates and phosphonates, as well as more active forms like orthophosphate diesters, labile orthophosphate monoesters, and organic polyphosphates Condron *et al*. (2005). Organic P becomes available to plants through mineralization, a biological process facilitated by soil microorganisms, plant root activity, and phosphate secretion. These processes are strongly influenced by environmental factors, including soil pH, moisture content, temperature, and the soil's physical and chemical properties.

The transformation and dynamics of phosphorus pools in soil are highly complex, requiring a holistic evaluation to fully understand their interactions and impact on phosphorus bioavailability Turner *et al.* (2007). By managing these dynamics effectively, agricultural practices can optimize phosphorus use, ensuring sustainable crop production and soil fertility.

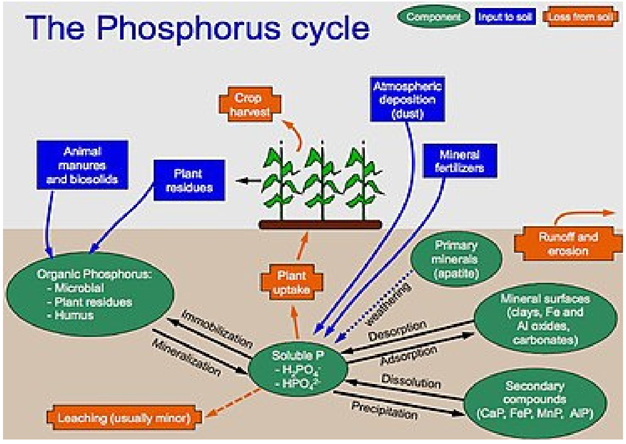

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Fig. 2 : Phosphorous dynamics in the soil

Factors affecting P-fixation in soils

(a) Amount of clay present and type of clay mineral

The soil's ability to fix phosphorus (P) is strongly influenced by the type and quantity of clay minerals present, including illite, vermiculite, halloysite, and kaolinite. These minerals play a significant role in phosphorus fixation due to their unique structural and chemical properties.

The primary mechanism behind the ability of clay minerals to fix phosphorus lies in the replacement of hydroxyl (OH^-) ions from their surfaces, particularly in the regions surrounding their crystalline structures. This creates reactive sites where phosphorus can interact. Additionally, phosphorus reacts with soluble aluminum (Al) released from exchange sites and lattice dissociation of clay minerals, leading to the formation of insoluble phosphorus compounds.

The process of phosphorus fixation by clay minerals can be categorized into two phases:

1. **Rapid Fixation**: This occurs due to the immediate interaction of phosphorus with easily accessible iron (Fe) and aluminum (Al) compounds present on the surfaces of the clay minerals.
2. **Gradual Fixation**: Over time, phosphorus reacts with Fe and Al ions that are slowly released during the breakdown of clay minerals. This process further stabilizes phosphorus in forms that are less available to plants.

The dynamics of phosphorus fixation by clay minerals demonstrate the complex interplay between soil chemistry, mineral composition, and environmental factors, ultimately influencing phosphorus availability for plant uptake.

a) Soil pH

Phosphorus fixation in soil exhibits high levels at both extreme acidic and alkaline pH values, significantly influencing its availability to plants. The solubility of basic iron (Fe) and aluminum (Al) phosphates is at its lowest around pH 3.0 to 4.0, where phosphorus remains tightly bound and less accessible. As soil pH increases, phosphorus begins to be released partially, reducing the soil's capacity to fix phosphorus. At pH 5.5, much of the inorganic phosphorus (Pi) is still chemically bonded with Fe and Al. When the pH approaches 6.0, phosphorus precipitation as calcium (Ca) compounds starts. Around pH 6.5, the formation of insoluble calcium-phosphate compounds further limits phosphorus availability. At pH levels above 7.0, even more insoluble substances, such as apatite, are formed, exacerbating phosphorus inaccessibility.

Two mechanisms have been identified as contributing to the reduction of phosphorus fixation with increasing pH:

Reversible Exchange: Phosphorus fixation results from a reversible exchange between hydroxyl ions in the crystal lattice and phosphate ions in solution. As hydroxyl ion concentration increases with rising pH, phosphorus fixation gradually diminishes.

Precipitation Processes: The precipitation of phosphate as Fe and Al phosphates further contributes to fixation. However, the activity of Fe and Al decreases steadily as pH rises, reducing the amount of phosphorus adsorbed by soil particles.

The availability of phosphorus for plant uptake is highly dependent on soil pH. Different phosphorus forms are absorbed more readily under specific pH conditions. In general, phosphorus availability is highest in soils with a pH range of 6.0 to 7.5. At pH values above 7.5, calcium and phosphorus react to form compounds that are less accessible to plants. Similarly, magnesium can interact with phosphorus at higher pH levels, resulting in various magnesium-phosphate complexes.

In acidic soils with pH values below 6.0, elevated levels of iron and aluminum significantly enhance phosphorus fixation or removal from the soil solution. At pH levels below 5.0, this process drastically reduces the availability of inorganic phosphorus, further hindering plant absorption.

Overall, soil pH plays a critical role in determining the availability of phosphorus for plants, with the optimal range for accessibility being between 6.0 and 7.5.

(c) Organic matter

Organic matter plays a significant role in reducing phosphorus (P) fixation in soils by interacting with iron (Fe) and aluminum (Al) compounds. Components such as lignin, humates, and aliphatic and aromatic hydroxy acids can inhibit or slow down the chemical reactions between phosphorus and Fe/Al, thereby enhancing P availability. When organic matter decomposes in water or through microbial activity, it further reduces phosphorus fixation by releasing compounds that interfere with P-binding processes.

The ability of clay minerals like kaolinite and montmorillonite to fix phosphorus depends on the type of surface coatings they possess. For example, iron oxide coatings enhance P fixation, while humic acid coatings reduce it. Soils with high levels of humic acid are particularly effective in minimizing P fixation. One strategy to improve phosphorus fertilizer efficiency involves either inhibiting P-fixing sites on Fe compounds using humic acid or maintaining the adsorption complex saturated with calcium (Ca) in a slightly acidic medium to create a high Ca/Fe ratio. This helps reduce phosphorus fixation and increase its availability to plants.

Humus, by binding soil particles together and partially saturating the secondary valences of the mineral lattice, further diminishes P fixation. The availability of P fertilizers can be significantly improved by incorporating organic inputs such as crop residues, green manures, or by combining superphosphate with organic manures before application. These practices enhance microbial activity, accelerating the breakdown of organic matter and making phosphorus more accessible to plants.

Organic colloids exhibit a much higher adsorption capacity for phosphate ions compared to inorganic soil colloids. This allows organic colloids to absorb phosphate ions, which are subsequently readily available for plant uptake. Additionally, superphosphate-treated manures decompose rapidly through microbial action, providing crops with an easily accessible source of phosphorus Dutti, (1961).

(d) Moisture

The moisture content of soil plays a critical role in influencing phosphorus (P) fixation and its transformations across various soil types. In alluvial and black soils, an increase in soil moisture has been shown to enhance the availability of phosphorus. Optimal soil moisture levels accelerate microbial activity, which, in turn, promotes the decomposition of organic matter and the subsequent release of phosphorus into the soil solution.

Adequate soil moisture also improves the soil's interaction with fertilizer solutions, facilitating better nutrient absorption by plants. Wet soil conditions not only enhance plant growth and development but also create a higher demand for phosphorus and other essential nutrients, particularly in areas with frequent rainfall or under irrigation. In these regions, crops often require increased levels of phosphorus to sustain their growth and maintain productivity.

The interplay between soil moisture and phosphorus availability underscores the importance of proper irrigation and water management practices in optimizing soil fertility and ensuring nutrient accessibility for crops.

(e) Temperature

Under sterile conditions, the rate of phosphorus (P) adsorption is highly temperature-dependent. When soil temperature increases from 250°C to 350°C, P retention shows minimal variation, indicating that such moderate changes have limited impact on P adsorption. However, optimal soil temperatures can significantly enhance microbial activity, which accelerates the decomposition of organic materials and subsequently increases the release of P into the soil solution.

At extreme temperatures, such as 10,000°C, the reaction rates associated with P adsorption increase dramatically. However, this rapid reaction does not necessarily result in greater overall P retention. This suggests that other factors, such as soil chemistry and mineral stability, may limit the efficiency of phosphorus fixation at exceptionally high temperatures.

Understanding the interaction between temperature and phosphorus dynamics highlights the critical importance of maintaining optimal soil temperatures for maximizing phosphorus bioavailability, especially under field conditions where microbial activity plays a central role.

Losses of Phosphorous from soils

Phosphorus loss from agricultural fields primarily occurs through three mechanisms: dissolution in surface water runoff, attachment to sediment carried by erosion, and dissolution in leachates transported through the soil profile. On cultivated fields, the majority of phosphorus loss results from erosion processes, whereas in non-tilled fields, phosphorus loss predominantly occurs through dissolution in surface water runoff or leachates. In phosphorus-rich soils, substantial amounts of phosphorus can still be lost, both in runoff and leachates.

Agricultural soils tend to either accumulate or lose phosphorus over time, depending on farming practices and soil management. Net phosphorus losses, often due to mining, can lead to reduced crop yields, lower soil productivity, and declining soil quality. To study and predict phosphorus dynamics in soils, the Environmental Policy Integrated Climate (EPIC) model is utilized (Fig. 3). This model simulates both organic and mineral components of soil phosphorus, categorizing mineral phosphorus into three pools: stable (fixed), active (loosely labile), and accessible (soluble). Of these, only water-soluble phosphorus compounds are directly available for plant uptake. The soluble and active pools are believed to achieve equilibrium relatively quickly (within days or weeks), while the stable and dynamic pools take longer to balance.

EPIC considers the influence of historical soil weathering, which determines the relative sizes of the active and stable pools in comparison to the soluble pool. Phosphorus from fertilizers is assumed to be soluble and evenly distributed to a specific depth in the soil, contributing directly to the soluble pool. Organic phosphorus is divided into two categories: the fresh residue pool, containing phosphorus from agricultural residues, manures, and microbial biomass; and the active and stable humus pools. Humic mineralization occurs exclusively in the active pool, releasing phosphorus into forms accessible to plants.

The EPIC model also accounts for changes within individual pools and interactions between organic and mineral fractions of soil phosphorus. To calculate phosphorus, use by plants, EPIC employs a supply-and-demand approach, balancing soluble phosphorus availability in the soil with the optimal phosphorus concentration required by plants on any given day.

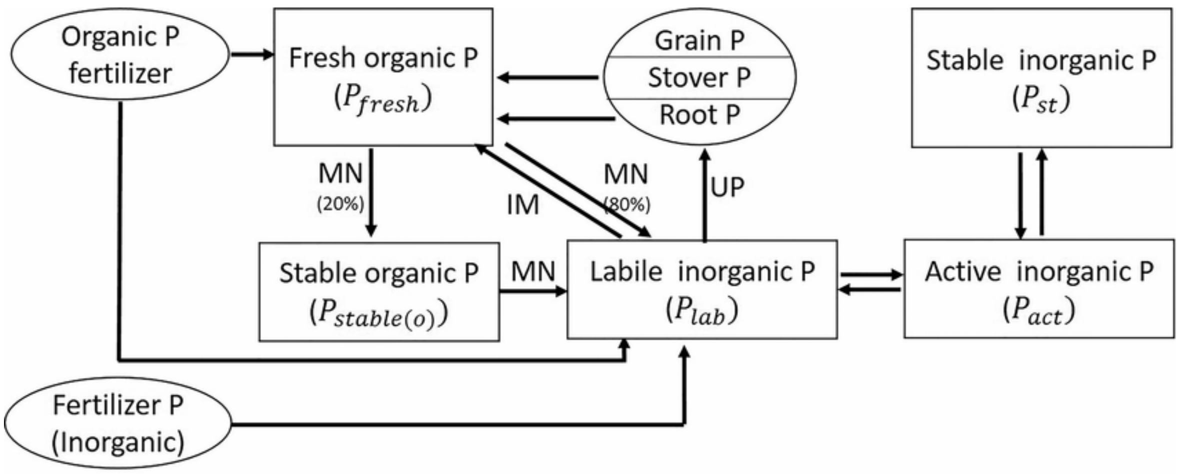

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Fig. 3 : Phosphorus cycle and loss as modelled in EPIC

Management practices to reduce P losses

During the initial weeks of crop growth, ensuring an adequate supply of phosphorus (P) is crucial for achieving optimal crop yield. In areas with soils rich in plant-available P, crops may absorb sufficient P directly from the soil to maximize growth at an affordable cost Nyborg *et al.* (1999). To determine the amount of P provided by the soil that is adequate for optimal plant development, various soil testing techniques are employed Follett *et al.* (1981). These tests help predict the soil's capacity to meet crop phosphorus demands under different environmental conditions.

The plant's ability to absorb sufficient P for sustained growth is influenced by several factors, including soil temperature, moisture content, and compaction. Effective nutrient management strategies must balance crop demand with soil nutrient availability to ensure plants receive the necessary levels of P during critical growth phases.

Phosphorus is relatively immobile in the soil and remains close to the site where fertilizers are applied. Compared to broadcast treatment, band placement of P fertilizers reduces soil interaction and minimizes fixation Tisdale *et al.* (1993). Band application commonly referred to as "starter P" is particularly beneficial in phosphorus-deficient soils with high P fixation capacities. By placing fertilizer bands near or alongside the seed during planting, phosphorus remains accessible to plants for a longer duration. Banding also improves the efficiency of phosphorus uptake by roots, reducing the potential for nutrient loss.

Ensuring proper placement of fertilizer bands is essential to prevent phosphorus from becoming "stranded" on the soil surface, especially in regions where soil dries out quickly. Roots cannot absorb nutrients from dry soil, making it imperative to position fertilizer in areas that retain sufficient moisture throughout the growing season. This targeted approach improves phosphorus availability and supports early crop development.

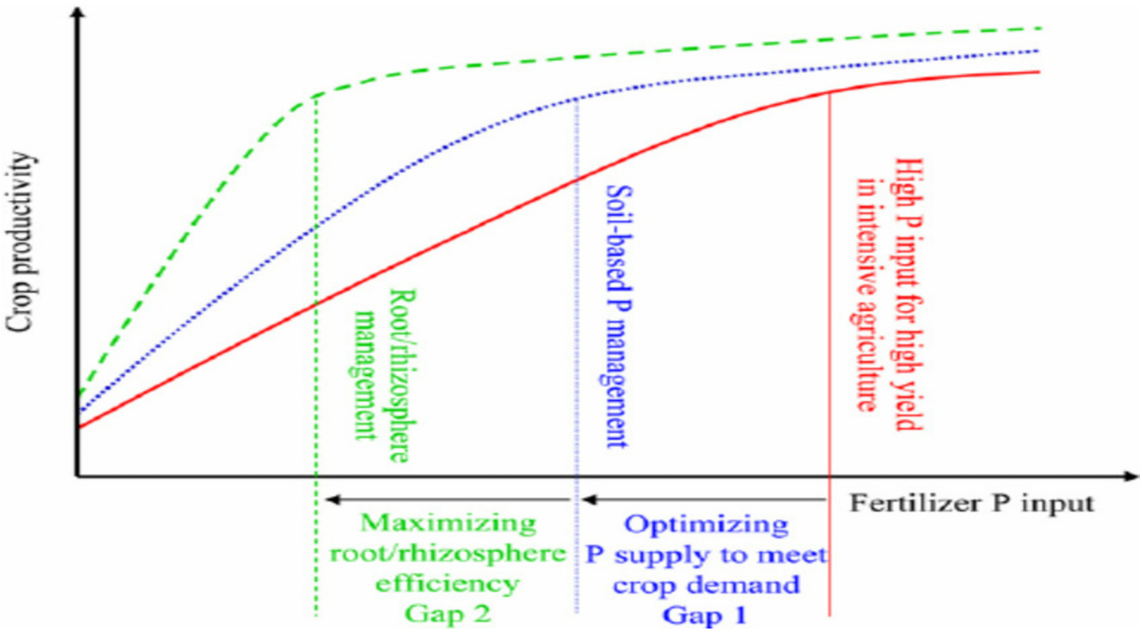
Phosphorus (P) placement is crucial for ensuring early contact with plant roots, particularly during the initial stages of the growing season, as phosphorus cannot easily move through the soil. When P fertilizers are positioned in a band near or within the seed-row, the highest concentration of roots can quickly contact and utilize the phosphorus soon after emergence. Directly seeding phosphorus fertilizers into the seed row or placing them in a side band has been shown to significantly boost wheat yields Swiader and Shoemaker (1998).

Conservation tillage and no-till practices also play a vital role in reducing soil erosion and phosphorus transport. Conservation tillage, which leaves 30% or more of the soil surface covered with crop residue after planting, and no-till, which covers 70% or more, effectively minimize nutrient loss. Longer crop rotations further reduce phosphorus application and loss while improving soil quality. Although extending rotations may lower wheat and soybean production in regions like Iowa, it could increase alfalfa output, supporting livestock production with high-quality feed and enhancing soil health.

Advancing knowledge of phosphorus dynamics in the soil, rhizosphere, and plant continuum is essential for improving phosphorus management and increasing its use efficiency in crop production. Effective phosphorus management integrates multi-level approaches, addressing interactions in the rhizosphere, plant, and soil systems. Optimization of phosphorus inputs on farmland can be achieved by balancing phosphorus applications with crop nutrient demands. Long-term phosphorus management plans are necessary due to its relative stability in soils, ensuring soil-available phosphorus is maintained at appropriate levels through regular monitoring of soil fertility.

On the North China Plain, studies have shown that implementing advanced phosphorus management strategies can reduce fertilizer application rates for high-yielding cereal crops by 20% compared to traditional farmer practices, conserving phosphorus resources without compromising crop yields Zhang *et al.* (2010). However, phosphorus buildup in soils may still occur due to high threshold levels and inefficient crop uptake. Rhizosphere-based phosphorus management (Fig. 3) an efficient solution by utilizing biological processes to mobilize and acquire phosphorus while reducing dependence on chemical fertilizers. In calcareous soils, localized application of phosphorus combined with ammonium has been shown to promote wheat growth by enhancing root proliferation and rhizosphere acidification Rui *et al.* (2010), demonstrating how rhizosphere processes can be modified at the field level to improve nutrient uptake and crop productivity.

Breeding cultivars or genotypes with improved phosphorus acquisition and utilization efficiency represents another approach for successful phosphorus management. Traits such as root exudates, enhanced root hairs, and topsoil foraging via basal or adventitious rooting have been identified as promising genetic characteristics for breeding phosphorus-efficient crops Singh Gahoonia and Nielsen (2004); Lynch and Brown (2001). These strategies collectively contribute to sustainable phosphorus management while maximizing crop yields and soil health.



https://www.researchgate.net/publication/51126218/figure/fig2/AS:305905238331393@1449944900043/Conceptual-model-of-root-rhizosphere-and-soil-based-nutrient-managements-for-improving.png

Fig. 4 : Conceptual models of root/rhizosphere and soil-based nutrient managements

Soil-based nutrient management offers a strategic approach to addressing Gap 1 by optimizing phosphorus (P) supply in soils to meet crop demands effectively. This method focuses on ensuring sufficient soil-available P, which can minimize the need for excessive P fertilizer applications, contributing to both economic and environmental sustainability.

Gap 2 can be bridged by utilizing root and rhizosphere management techniques, which aim to enhance crop yield and phosphorus-use efficiency. By leveraging processes such as rhizosphere acidification, improved root proliferation, and enhanced microbial activity, these strategies further reduce the reliance on external phosphorus inputs while maintaining high productivity. This dual approach emphasizes balancing soil dynamics with biological potential for sustainable nutrient management.

Summary and Conclusion

To maximise crop output, wheat needs a sufficient amount of P in the early stages of development. In order to improve their capacity to both acquire and utilise available P for the generation of viable seed, plants have evolved a variety of techniques. In order to guarantee that the crop receives sufficient amounts of accessible P throughout the early phases of crop growth, it is critical to identify P deficiencies and control cropping systems. In order to do this, it is necessary to acknowledge how management decisions may affect the biological and physical properties of the soil, which may have an impact on crops' early-season P availability. Among the management strategies that may be used to maximise P nutrition include band placement of P fertiliser in or near the seed-row and maintenance of soil P levels by long-term fertiliser management. More extensive effects are shown by phosphorus on agricultural and natural environments. Because phosphorus is withdrawn from the system in harvested crops and only a small amount is restored in crop residues and animal manures, phosphorus restrictions are significantly more severe in agricultural ecosystems Brady and Weil (2002). In soils, phosphorus is not as common as nitrogen and potassium. The amount of total P in surface soils ranges from 0.005 to 0.15 percent, and regrettably, there is little to no correlation between soil total P content and plant P availability Havlin *et al.* (1999). A sharp reduction in production was eventually caused by soils' high P fixing capability and inherent P deficit. This means that in order to fulfil the crops' requirement for P nutrients, greater inputs must be used. The P dynamics in the soil, rhizosphere, and plant continuum primarily regulate the P nutrition of plants. There is a large amount of geographical and temporal variation in the dynamics and distribution of P in soil. A crucial factor in effectively using these P resources is root design, which disperses additional roots to the location of P resources. Additionally, in the mobilisation and acquisition of P, root architecture may display functional coordination with root exudation of protons, phosphates, and carboxylase. Increased soil P availability and bioavailability can be achieved by coordinating plant adaptations in root shape and physiology to P-limiting situations. This can successfully match heterogeneous P supply and dispersion. A better understanding of P availability, movement in the soil, fixation, and dynamics in the soil/rhizosphere-plant continuum is required given the importance of P to plants and as a strategic resource. This understanding will help guide the establishment of integrated P-management strategies that will involve manipulating soil and rhizosphere processes, developing P-efficient crops, and enhancing P-recycling efficiency in the future.

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