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Review on Effect of Phosphorous Fertilizer and Its Availability on Growth and Development of Maize (Zea mays L.)

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Abstract
Maize (Zea mays L.) is an important cereal crop in the world. Low soil fertility is recognized as the major constraint to low maize production and productivity. Phosphorus (P) is an essential nutrient element for maize production. It plays an important part in many physiological processes that occur within a developing and maturing plant. It exists in the soil solution as an anion in various forms, mono-hydrogen phosphate (HPO_4^{-2}) or di-hydrogen phosphate ($H_2PO_4^-$) depending on the soil pH. Phosphorus fertilization is a major input in crop production, as many soils lack sufficient P for effective crop production. Plants need phosphorus for growth, utilization of sugar and starch, photosynthesis, nucleus formation and cell division. An adequate supply of available P in soil is associated with increased root growth, which means roots can explore more soil for nutrients and moisture. A deficiency of P will slow overall plant growth and delay crop maturity. Phosphorus is primarily lost from farm fields through attachments to the sediment that erodes from the field, dissolved in the surface water runoff, or dissolved in leachates and carried through the soil profile. Nutrient management practices must be designed to supply required nutrients to the plant, taking into account the balance between crop demand and supply from the soil, development of P-efficient crops, and improving P-recycling efficiency in the future.
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1. Introduction

Maize (*Zea mays L.*) is an important cereal crop in the world which ranks the third in production after wheat and rice. Maize is grown widely in many countries of the world. The major yield producers are the United States, Brazil, France, India and Italy. In Africa, the bulk of maize produced is used as human food although it is increasingly been utilized for livestock feed. According to FAOSTAT [1] (Food and Agricultural Organization) data, there was an increased maize production from 499,210 hg/ha in 1961 to 855,422 hg/ha in Africa. Overall, there has been a 71.35% increase in maize yield across Africa. As concerns harvest area, Africa has witnessed a 60.12% increase in harvest area from 23,637,839 ha in 1961 to 37,847,719 ha in 2019. Since 1961, maize production on a global scale has increased from 205 M tons to 1145 M tons [1].

In spite of the increase in land areas under maize production, yield is still low in Africa. Some of the major causes of low maize yield are declining soil fertility and insufficient use of fertilizers resulting in severe nutrient depletion of soils. Maize requires adequate supply of nutrients particularly nitrogen, phosphorus and potassium for good growth and high yield.

Phosphorus plays an important part in many physiological processes that occur within a developing and maturing plant. It is involved in enzymatic reactions in the plant. Phosphorus is essential for cell division because it is a constituent element of nucleoproteins which are involved in the cell reproduction processes. It is also a component of a chemical essential to the reactions of carbohydrate synthesis and degradation. It is important for seed and fruit formation and crop maturation. Phosphorus hastens the ripening of fruits thus counteracting the effect of excess nitrogen application to the soil. It helps to strengthen the skeletal structure of the plant there by preventing lodging. It also affects the quality of the grains and it may increase the plant resistance to diseases. However, the requirement and utilization of this nutrient (phosphorus) in maize depends on environmental factors like rainfall, varieties and expected yield.

Phosphorous is an essential plant element classified as a major element. It is a component of several enzymes and proteins and an element involved in various energy transfer systems in the plant. Phosphorus exists in the soil solution as an anion in various forms, mono-hydrogen phosphate (HPO_4^{-2}) or di-hydrogen phosphate ($H_2PO_4^-$) depending on the soil pH. Phosphorus is classified as a fertilizer element, being the second ingredient given in percent content as the phosphorus pentoxide (P_2O_5) form.

Phosphorus fertilization is a major input in crop production, as many soils lack sufficient P for effective crop production. To optimize crop nutrition, P must be available to the crop in adequate amounts early in the growing season. Phosphorus is needed from the earliest stages of crop growth, because it is important in nearly all energy-requiring processes in the plant. Phosphorus stress early in the growing season will reduce crop productivity more than P restrictions later in the year. In general this paper was aims to review the effect of

Phosphorous fertilizer on maize growth and development.

2. Literature review

2.1. Phosphorous availability to maize crop

Phosphorous is exists in most soils in about equal amounts of organic or inorganic forms. Di-hydrogen phosphate (H_2PO_4) and mono-hydrogen phosphate (HPO_4^{2-}) are the two anion forms of P in the soil solution, which form and their concentration depending on soil water pH. Al, Fe, and Ca phosphates are the major inorganic sources of P, the relative amount among these three forms being a function of pH soil water. Release of P into the soil solution with the decomposition of crop residues and microorganisms can be a major source of P for plant utilization. Plant availability is influenced by pH of soil water.

2.2. Roles of Phosphorous in maize growth and development

2.2.1. Storage and transfer of energy

Plants need phosphorus for growth, utilization of sugar and starch, photosynthesis, nucleus formation and cell division. Phosphorus compounds are involved in the transfer and storage of energy within plants. Energy from photosynthesis and the metabolism of carbohydrates is stored in phosphate compounds for later use in growth and reproduction. Phosphorus is readily trans-located within plants, moving from older to younger tissues as the plant forms cells and develops roots, stems and leaves. Adequate P results in rapid growth and early maturity, which is important in areas where frost is a concern. Frequently, P will enhance the quality of vegetative crop growth.

2.2.2. Phosphorous for maize growth

Phosphorus is a critical nutrient for maize growth, since it is involved in cellular energy transfer, respiration, and photosynthesis. Phosphorus is also a structural component of the nucleic acids of genes and chromosomes and of many coenzymes, phospho-proteins and phospholipids [2]. An adequate supply of P is essential from the earliest stages of the maize crop growth. Early season deficiencies of P can lead to restrictions in the crop growth from which the plant will not recover, even when P supply is increased to adequate levels.

This element plays also a role in an array of processes including energy generation, nucleic acid synthesis, photosynthesis, glycolysis, respiration, membrane synthesis and stability, enzyme activation/inactivation, redox reactions, signaling, carbohydrate metabolism, and nitrogen fixation.

In young, actively growing plants, P is most abundant in the actively growing tissue. By the time plants have attained about 25 per cent of their total dry weight, they may have accumulated as much as 75% of their total phosphorus requirements. Therefore, maize requires significant quantities of P during the early stages of growth.

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An adequate supply of available P in soil is associated with increased root growth, which means roots can explore more soil for nutrients and moisture. Phosphorus occurs in most plants in concentrations between 0.1 and 0.4 per cent, on a dry weight basis. A deficiency of P will slow overall plant growth and delay crop maturity.

Due to relatively low P level in soil, marked yield responses in maize have been obtained with P application. Soil P availability is critical for early growth and development of maize because it affects root morphological and physiological characteristics that are important for P uptake [3]. Sharif Zia *et al.* [4] found that maize dry matter yield, P tissue concentration and P uptake were significantly affected by varying rates of P. Consequently, the critical and toxic limits of P for maize growth were found to be below 1.4 mg g-1 (0.14 %) and above 3.6mg g-1 (0.36 %) dry matter, respectively.

2.2.3 Forms of P taken up by the maize

The form of P applied as fertilizer may be as the orthophosphate anion (PO_4^{-3}), the diphosphate anion ($H_2PO_4^-$), or the mono phosphate anion (HPO_4^{-2}), depending on the fertilizer chemical composition. Phosphorus availability for root absorption is a complex process of interacting soil chemistries. Even though a highly soluble form of P is applied, such as phosphoric acid (H_3PO_4), the orthophosphate anion (PO_4^{-3}) will quickly interact with the soil, forming precipitates with the elements Ca, Fe, and Al, and that remaining in soluble form will exist in the soil solution as either the diphosphate anion ($H_2PO_4^-$) or as the mono-phosphate anion (HPO_4^{-2}), depending on the pH of the soil, and moves primarily in the soil solution by diffusion.

Which form of phosphorus exists in the nutrient solution will depend on pH, di-hydrogen phosphate ($H_2PO_4^-$) and mono-hydrogen phosphate (HPO_4^{-2}) in acid solutions and triphosphate (PO_4^{-3}) in nutrient solutions when the pH is approaching alkalinity (pH > 7.0). Because the concentrations of these ions in soils are in the micro-molar range, high-affinity active transport systems are required for P uptake against a steep chemical potential gradient across the plasma membrane of root epidermal and cortical cells.

2.2.4. Deficiency of P in Maize

Phosphorus deficiency can reduce both respiration and photosynthesis but, if respiration is reduced more than photosynthesis carbohydrates will accumulate, leading to dark green leaves [5]. Also plants become dark green to purplish in color [6]. A deficiency can also reduce protein and nucleic acid synthesis, leading to the accumulation of soluble nitrogen compounds in the tissue, and ultimately resulting in cell growth being delayed and potentially stopped. As a result, symptoms of P deficiency i.e. decreased plant height, delayed leaf emergence, slow-growing, weak, and stunted plants that may be dark green in color with older leaves showing a purple pigmentation. Being fairly mobile in the plant, P-deficiency symptoms initially occur in the older tissue.

Plant roots typically respond to P deficiency through allocation of more carbon to roots, resulting in increased root growth, enhanced lateral root formation, greater exploration of the surface soil, increased length and number of root hairs [7,8,9]. The length of time required for a P deficiency to affect growth depends on the extent of P reserves in the plant. An adequate supply of available P in soil is associated with increased root growth, which means roots can explore more soil for nutrients and moisture. A deficiency of P will slow overall plant growth and delay maize crop maturity.

A mild P deficiency results in somewhat stunted crop growth, which can be difficult to see. In severe cases of P deficiency, symptoms include characteristic stunting, purpling or browning, appearing first on the lower leaves and base of the stem and working upward on the plant, particularly on cereal crops. The effect is first evident on leaf tips, and then progresses toward the base. Eventually, the leaf tip dies. However, visual diagnosis of P deficiency is very difficult and must be confirmed with soil tests and possibly with the aid of plant tissue analysis. Symptoms are most pronounced in young plants because their more rapid growth makes greater demands on the available supply. Crops seldom completely outgrow a P deficiency; the symptoms often persist to delay maturity.

2.3. Phosphorous fixation capacity of soils

The P fixation is a process whereby the readily soluble forms of P are changed to sparingly soluble forms by reacting with inorganic and organic components of soils or by other means thus restricting the availability of P to the plants. Fixation is a generic word used to designate the transformation of soluble soil phosphate forms into insoluble ones. Any phenomenon that causes a decrease in the orthophosphate ion concentration in a solution in contact with the soil is responsible for the fixation. In other words, both iron and aluminum compounds (hydrated oxides) present in the soil are the main responsible for the phosphorus "fixation".

The amount of phosphorus fixed by a soil depends on a series of factors, as: phosphate concentration in the solution, solution pH, reacting time, temperature, relation between the weight of the soil sample and the volume of the solution, and physico-chemical characteristics of the soil itself.

Fixation of P by soils has long been recognized. Differences of opinions have, however, been expressed from time to time by various workers regarding the manner in which P is fixed by the soils. It is suggested that probably three separate mechanisms, which possibly overlap each other, are responsible for P fixation. At pH 2 to 5 the retention of P is chiefly due to the gradual dissolution of Fe· and AI oxides which are re precipitated as phosphates. At pH 4.5 to 7.5, P is fixed on the surface of the clay particles and at pH 6 to 10; P is precipitated by the divalent cation. No single mechanism is responsible for P fixation in all soils.

2.3.1. Phosphorous content of soils

The phosphorus available to plants can be assessed by measuring the phosphate concentration in the soil solution and the soil's ability to maintain the soil solution concentration. The quantity of P in the soil solution, even when at relatively high levels, is only in the range of 0.3 to 3.0 kg ha^{-1} (0.3 - 3.0 lb ac^{-1}). Rapidly growing crops will absorb about 1 kg ha^{-1} (1.0 lb ac^{-1}) of P per day. Therefore, soil solution P must be replenished by the "labile" pool of soil P. Labile P is a pool of soil P that is less available to plants but can undergo rapid chemical or biological changes to recharge or replenish the available P.

It is also important to note that P levels in some soils have increased over the years as a result of repeated annual commercial fertilizer P application or frequent livestock manure application. Consequently, maize grown on some soil types, with higher versus lower soil P levels, are less responsive to fertilizer P application. Additionally, factors such as rate of P fertilizer applied and method of application used can all affect P uptake of the maize.

Maize response to applied P fertilizer depends, to a large extent, on the quantity of plant-available P already in the soil. The soil test ratings are normally based on a 0 to 15 cm (0-6 inch) sample depth because P is not very mobile in the soil. Therefore, the concentration of P is greatest in the surface soil.

Phosphorus is temporarily tied up in the organic components of micro-organisms; however, this P is eventually returned to the soil when microbes die and break down. After mineralization (conversion from organic P to inorganic P), soil P can be taken up by plants.

In more acidic soils (pH< 6.0) iron and aluminum increase, which causes either a fixing or removing of P from the soil solution. This action greatly limits the availability of inorganic P to plants at soil pH levels <5.0.

2.3.2. Sources of phosphorous

Both the liquid and granular sources of fertilizer listed in Table 1 provide the same inorganic forms of P: $H_2PO_4^-$ or HPO_4^{-2}. These two forms are commonly referred to as orthophosphate and are the form of P that is used by most crops. The choice of P fertilizer source depends on economics, equipment availability or farmer preference, and local fertilizer supply. The source of P makes no difference to plants.

Table 9 Sources of Phosphorous

Source	Formula	Form % Available P_2O_5	
		Citrate soluble	Water soluble
Superphosphate(0N-20P-0K)	$Ca(H_2PO_4)2$	Solid	90
Concentrated superphosphate (0N-45 P_2O_5-0K)	$Ca(H_2PO_4)2$	Solid	92–98
Mono-ammonium phosphate (11 N-52P_2O_5-0K_2O)	$NH_4H_2PO_4$	Solid	100
Di-ammonium phosphate (18 N-46P_2O_5-0K_2O)	$(NH_4)2HPO_4$	Solid	100
Ammonium polyphosphate	$(NH_4)\ 2HP_2O_7 \times H_2O$	Solid	100
Phosphoric acid	H_3PO_4	Liquid	100
Rock phosphate, fluor- 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	—

2.3.3. Movement of Phosphorous in the soils

Phosphate ($H_2PO_4^-$ and HPO_4^{-2}) anions are brought in contact with the root surface primarily by diffusion in the soil solution (Figure 1). Root interception and the abundance of root hairs will significantly increase the opportunity for P absorption. Cool soil temperatures and low soil moisture contents can reduce P uptake, and therefore create a P deficiency.

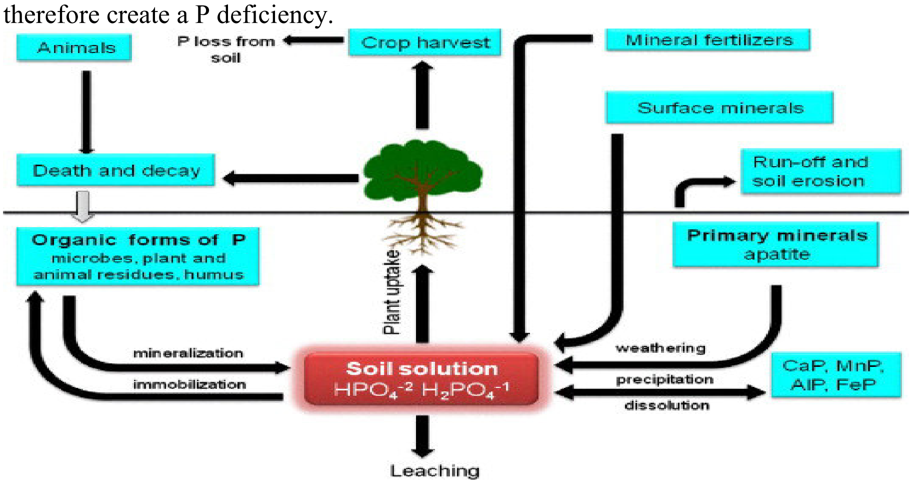


Figure 1 Movement of Phosphorous in the soils

2.3.4 Phosphorus dynamics in the soils

Soil P exists in various chemical forms including inorganic P (Pi) and organic P (Po). These P forms differ in their behavior and fate in soils [10, 11]. Pi usually accounts for 35% to 70% of total P in soil as calculation from Harrison [12]. Primary P minerals including apatites, strengite, and variscite are very stable, and the release of available P from these minerals by weathering is generally too slow to meet the crop demand though direct application of phosphate rocks (i.e. apatites) has proved relatively efficient for crop growth in acidic soils. In contrast, secondary P minerals including calcium, iron, and aluminum phosphates vary in their dissolution rates, depending on size of mineral particles and soil pH [13, 14]. With increasing soil pH, solubility of Fe and Al phosphates increases but solubility of Ca phosphate decreases, except for pH values above 8 [15]. The P adsorbed on various clays and Al/Fe oxides can be released by desorption reactions. All these P forms exist in complex equilibria with each other, representing from very stable, sparingly available, to plant-available P pools such as labile P and solution P (Figure 1).

Soil Po mainly exists in stabilized forms as inositol phosphates and phosphonates, and active forms as orthophosphate diesters, labile orthophosphate monoesters, and organic polyphosphates [11, 16]. The Po can be released through mineralization processes mediated by soil organisms and plant roots in association with phosphates secretion. These processes are highly influenced by soil moisture, temperature, surface physical chemical properties, and pH of soil. Po transformation has a great influence on the overall bioavailability of P in soil [17]. Therefore, the availability of soil P is extremely complex and needs to be systemically evaluated because it is highly associated with P dynamics and transformation among various P pools (Figure 2).

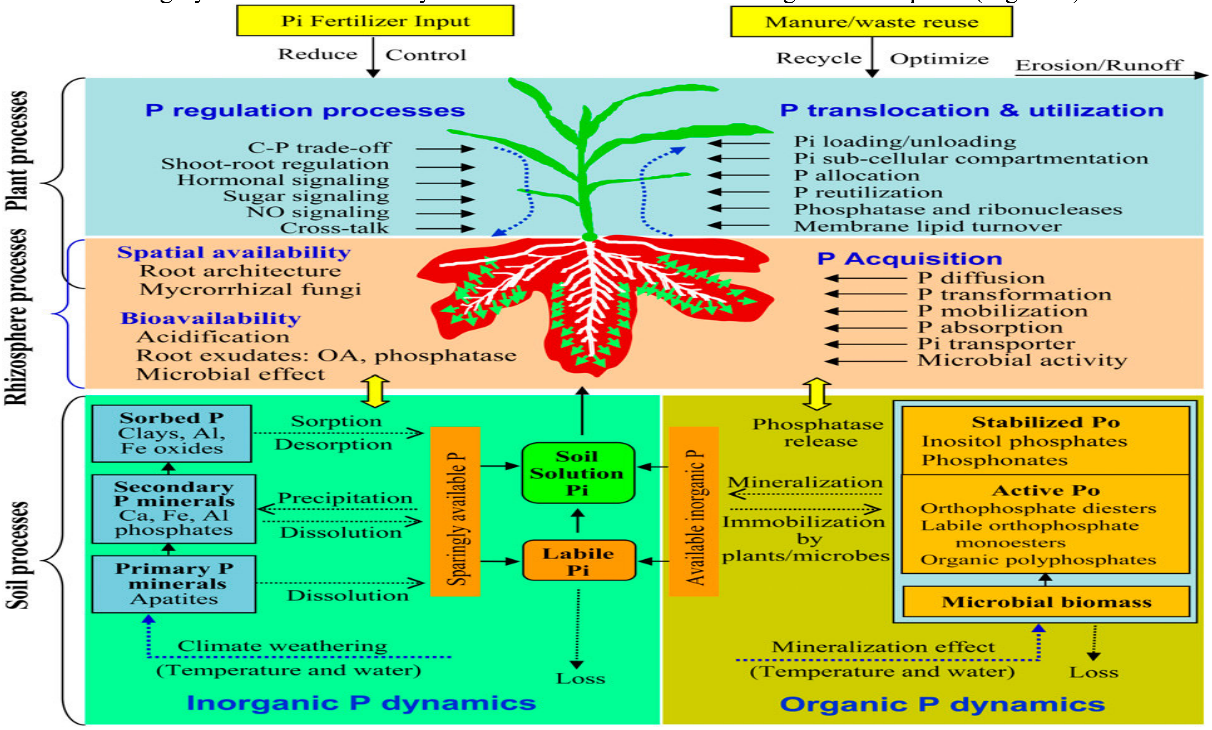


Figure 2 Phosphorous dynamics in the soil/rhizosphere-plant continuum
Source: www.plantphysiol.org Copyright © 2011 American Society of Plant Biologists

2.4. Factors affecting P-fixation in soils

2.4.1. Amount of clay present and type of clay mineral

The amount and nature of clay minerals of soil such as kaolinite, halloysite, montmorillonite, vermicullite and illite are the most potent factors determining the P fixing capacity. The P fixing capacity of the clay minerals is mainly due to the replacement of OH ions from the clay minerals surface, especially around the crystal edges and P reaction with soluble Al originating from the exchange sites and from lattice dissociation, of clay minerals to form insoluble P compounds. The rapid P fixation by the clay minerals is attributed to its reaction with readily available Fe and Al and slow fixation from the reaction of P with Fe and Al released through decomposition of the minerals.

2.4.2. Soil pH

Fixation of P in soil is generally high at low and high pH. The basic Fe and Al phosphate have a minimum solubility around pH 3.0 to 4.0. At higher pH some of the P is released and the P fixing capacity is somewhat reduced. Even at pH 5.5 much of the Pi still chemically combined with Fe and AI. As the pH approaches 6.0 precipitation of P as Ca compounds begins; at pH 6.5, the formation of insoluble Ca-P is a factor in rendering the P unavailable. Above pH 7.0 even more insoluble compounds such as apatite are formed.

The decrease in P fixation with increase in pH was attributed to two mechanisms; viz. (i) P fixation was due to reversible exchange between phosphate ion in solution and hydroxyl ion of the crystal lattice. As the hydroxyl ion concentration in solution increased, the above reaction gets inhibited; resulting in a progressive decrease in P fixation, (ii) P fixation was owing to the precipitation of phosphate as Fe and Al phosphate. As the pH increased, the activity of Fe and Al was gradually reduced and consequently the amount of adsorbed P decreased.

Plant availability of P can be affected by soil pH. For example, some P forms are absorbed more readily than other forms. Generally, soil P is slightly more available in a pH range of 6.0 to 7.5 pH. At higher pH levels (>7.5), calcium may react with phosphorus, creating forms that have slightly lower availability to plants. Magnesium acts in the same manner, forming different types of magnesium phosphate compounds. In more acidic soils (pH<6.0), iron and aluminum increase which causes either a fixing or removing of P from the soil solution. This action greatly limits the availability of inorganic P to plants at soil pH levels <5.0. As general rule the maximum availability of P occurs in soils within a pH range of 6.0 to 7.5.

2.4.3. Organic matter
The aliphatic and aromatic hydroxy acids, humates and lignin components of organic matter can prevent or reduce the chemical combination of P with Fe and Al. The decomposition of organic matter by H_20 or through microbial activity decreases the P fixation. P fixation capacity of kaolinite and montmorillonite depends upon the nature of their surface coatings; iron oxide coating increased whereas humic acid coating decreased the P fixation. The presence of large amount of humic acid in soil decreases P fixation. A large Ca/Fe ratio which increases the efficiency of P fertilizer can be obtained either by keeping the adsorption complex saturated with Ca in a slightly acid medium or by blocking the P fixing sites of Fe compounds with humic acid.

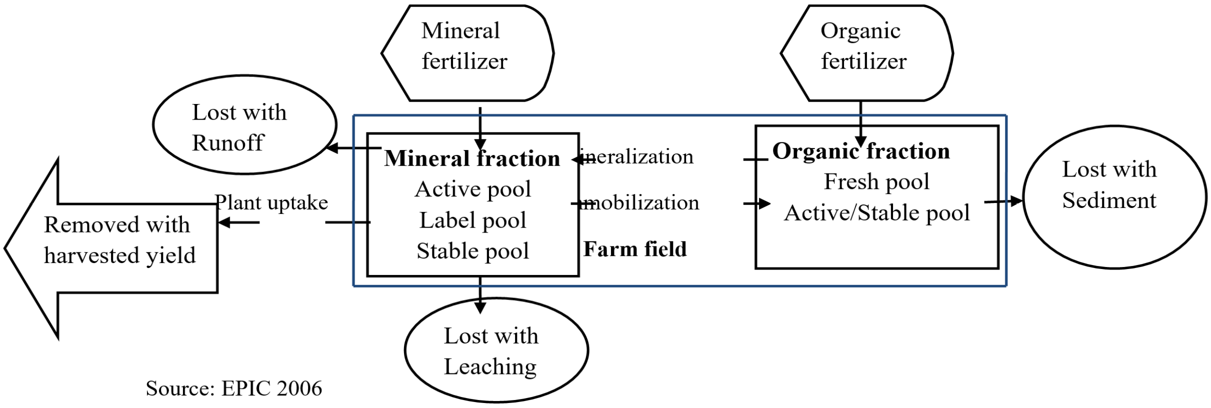
The presence of humus decreased the P fixation partially by saturating the secondary valences of the mineral lattice and partially by cementing the soil particles together. The addition of crop residues and green manuring or mixing of superphosphate with organic manure before its application increased the availability of P fertilizers [18]. The phosphate ions are absorbed by the organic colloids because organic colloids have many times higher adsorption capacity than inorganic soil colloids. The phosphate ion adsorbed by organic colloids is easily available to plants. The superphosphate treated manures added to the soil undergo rapid microbial decomposition and make their P readily available to crops.

2.4.4. Moisture
The P fixation and transformations in different soils are greatly influenced by the moisture of the soil. The available P increased with increase in soil moisture in black and alluvial soils. Optimal soil moisture can help accelerate microbe activity, thereby releasing more P from organic matter. Adequate soil moisture will enhance fertilizer solution and reaction in the soil. As well, moisture will promote plant growth, so P and other nutrient requirements are generally higher for crops grown under irrigation or in higher rainfall areas.

2.4.5. Temperature
The rate of P adsorption is temperature dependent under sterile conditions. P retention increased only slightly as the temperature is increased form 25^0C to 35^0C. Optimal soil temperature can help accelerate microbe activity, thereby releasing more P from organic matter. If the temperature is increased up to $l00^0$C, the reaction proceeded much more rapidly but the total retention of P may not increase.

2.5. Losses of Phosphorous from soils
Phosphorus is primarily lost from farm fields through three processes: attached to the sediment that erodes from the field, dissolved in the surface water runoff, or dissolved in leachates and carried through the soil profile. On cultivated fields, most is lost through erosion, whereas on non-tilled fields most phosphorus losses are dissolved in surface water runoff or in leachates. Cultivated acres with phosphorus-rich soils, however, can also lose significant amounts of phosphorus dissolved in the runoff or the leachates.

Over years of farming, cropland soils tend to either gain or lose phosphorus. In cases where soils experience net losses (mining), reductions in soil quality, soil productivity, and crop yields can be expected to follow. EPIC (Environmental Policy Integrated Climate) simulates mineral and organic fractions of soil phosphorus. The mineral fraction consists of available (soluble), active (loosely labile), and stable (fixed) pools. Only phosphorus compounds that are soluble in water are available for plants to use. The soluble and active pools are assumed to be in rapid equilibrium (several days or weeks). The soluble pool is input and the size of the active and stable pools relative to the soluble pool is set by EPIC based on the amount of past soil weathering. The active pool is in slow equilibrium with the stable pool. Fertilizer phosphorus is assumed to be in soluble form which is mixed uniformly to a specific depth. Thus, fertilizer phosphorus contributes directly to the soluble pool. Organic phosphorus is divided into the fresh residue pool, consisting of phosphorus in the microbial biomass, manures, and crop residues, and the active and stable humus pools. Humic mineralization occurs in the active pool only. The model accounts for transformations between pools within each fraction and also between the organic and mineral fractions. Plant use of phosphorus is estimated using the supply and demand approach, which balances soluble phosphorus in the soil with an ideal phosphorus concentration in the plant for a given day.



Source: EPIC 2006

Figure 3 Phosphorus cycle and loss as modeled in EPIC

2.6. Management practices to reduce P losses

For optimum crop yield, P supply must be adequate during the first few weeks of growth. Where the supply of plant-available P in the soil is high, the soil may supply sufficient P to the plant to optimize economic crop yield [19]. A wide number of soil testing methods are used in an attempt to predict the adequacy of soil-supplied P for optimum plant growth [20]. However, specific plant factors as well as environmental factors such as soil temperature, moisture, and compaction, will all influence the ability of the plant to absorb sufficient P to support optimum growth. Nutrient management practices must be designed to supply required nutrients to the plant, taking into account the balance between crop demand and supply from the soil.

Phosphorus is relatively immobile in the soil and so remains near the site of fertilizer placement. Band placement of P reduces contact with the soil and should result in fewer fixations than broadcast application [21]. In P-deficient soils with a high P fixation capacity, the optimal method of supply P for early crop growth is generally by banding the fertilizer near to or with the seed, during the seeding operation (i.e. use of “starter P”). While banding may maintain P in a plant-available form for a longer period of time, it can also improve the ability of plants to utilize fertilizer P. As roots cannot take nutrients up from dry soil, placing the band in a position where the soil does not dry out early in the season avoids having the fertilizer "stranded" on the surface of the soil where the roots cannot use it.

Since P will not move through the soil, it must be placed in a position where the plant roots can contact it early in the season. Placing the P in a band in or near the seed-row allows the highest possible concentration of roots to contact and utilize the band soon after emergence. Therefore, fertilizer P is most efficiently used when seed-placed or placed in a band close to the seed. Maize yields were increased with seed-row or side-banded P fertilizer [22].

Conservation tillage, where 30% or more of the soil surface is covered with crop residue after planting, or no-till, where 70% or more of the soil surface is covered with crop residue after planting, reduces soil erosion and surface runoff also reduces P transport.

Extended rotations reduce the application and the loss of both P. If a shift to extended rotations is significant, the amount of corn and soybean produced in Iowa would be reduced, along with an increase in alfalfa production that could support increased livestock production for alfalfa feeding. Another benefit would be improved soil quality.

Better understanding of P dynamics in the soil/ rhizosphere-plant continuum provides an important basis for optimizing P management to improve P-use efficiency in crop production. The effective strategies for P management may involve a series of multiple-level approaches in association with soil, rhizosphere, and plant processes. P input into farmland can be optimized based on the balance of inputs/outputs of P. Soil-based P management requires a long-term management strategy to maintain the soil-available P supply at an appropriate level through monitoring soil P fertility because of the relative stability of P within soils. By using this approach, the P fertilizer application can be generally reduced by 20% compared to farmer practice for the high-yielding cereal crops in the North China Plain [23]. This may be of significant importance for saving P resources without sacrificing crop yields (Figure 4) though it may cause P accumulation in soil due to high threshold levels and low P-use efficiency by crops.

Rhizosphere-based P management provides an effective approach to improving P-use efficiency and crop yield through exploitation of biological potential for efficient mobilization and acquisition of P by crops, and reducing the overreliance on application of chemical fertilizer P (Figure 4). Localized application of P plus ammonium improved maize (Zea mays) growth by stimulating root proliferation and rhizosphere acidification in a calcareous soil, indicating the potential for field-scale modification of rhizosphere processes to improve nutrient use and crop growth [24].

Alternatively, successful P management can be achieved by breeding crop cultivars or genotypes more efficient for P acquisition and use. Some important root genetic traits have been identified with potential utility in breeding P-efficient crops, including root exudates, root hair traits, topsoil foraging through basal, or adventitious rooting [25, 26].

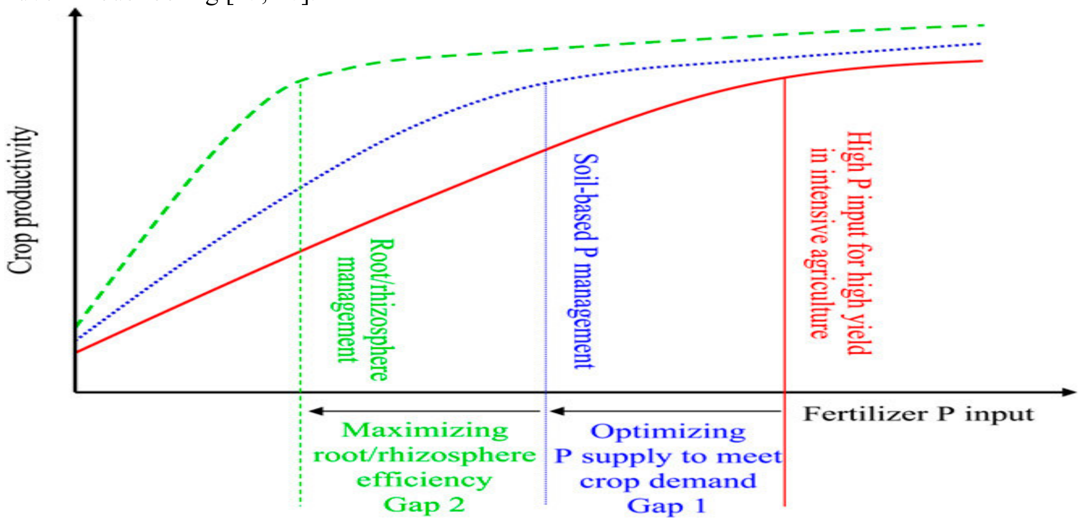


Figure 4 Conceptual models of root/rhizosphere and soil-based nutrient managements

Gap 1 for saving P input can be achieved by soil-based nutrient management for optimizing P supply to meet crop demand. Gap 2 can be realized by root/rhizosphere management for improving P-use efficiency and crop production through exploitation of root/rhizosphere efficiency and further saving P resource input. The red line (solid curve) represents crop productivity response to high-P input under intensive agriculture. The blue line (dotted curve) represents crop productivity response to P input under soil-based P management. The green line (dashed curve) represents crop productivity response to P input under root/rhizosphere management.

3. Summary and conclusion

Maize requires an adequate P supply during the early stages of growth to optimize crop yield. Plants have evolved strategies to enhance their ability to access and utilize available P for the production of viable seed. It is important to recognize P deficiency and to manage cropping systems to ensure adequate levels of available P are provided to the crop during the early stages of crop growth. This requires recognition of the potential effects of management practices on soil physical and biological characteristics that can influence the early season availability of P to crops. Band placement of P fertilizer in or near the seed-row and maintenance of soil levels of P through long-term fertilizer management are among the management practices that can be adopted to optimize P nutrition.

Phosphorus has more wide spread influence on both natural and agricultural ecosystems. In agricultural ecosystems, phosphorus constraints are much more critical because phosphorus is removed from the system in the harvested crops with only limited quantities being returned in crop residues and animal manures [27]. Phosphorus does not occur as abundantly in soils as N and K. Total P in surface soils varies between 0.005 and 0.15 % and unfortunately the quantity of total P in soils has little or no relationship to the availability of P to plants [28].

Inherent P deficiency and high P fixation capacity of soils eventually led to severe yield decline. This calls for using more inputs to meet the P nutrient demand of crops. The P nutrition of plants is predominantly controlled by P dynamics in the soil /rhizosphere- plant continuum. The distribution and dynamics of P in soil has a significant spatial and temporal variation. Root architecture that distributes more roots to the place where P resources are located plays an important role in efficiently exploiting these P resources. Furthermore, root architecture can exhibit functional coordination with root exudation of carboxylase, protons, and phosphates in P mobilization and acquisition. The coordination of plant adaptations in root morphology and root physiology to P-limiting environments may effectively match heterogeneous P supply and distribution in soil, resulting in increased spatial availability and bioavailability of soil P.

Given the importance of P to plants and its importance as a strategic resource, a better understanding of P availability, movement in the soil, fixation and dynamics in the soil/rhizosphere-plant continuum is necessary to guide establishment of integrated P-management strategies involving manipulation of soil and rhizosphere processes, development of P-efficient crops, and improving P-recycling efficiency in the future.

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