Chapter

Sustainable Management of Phosphorus in Agriculture for Environmental Conservation

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Abstract

Phosphorus (P) is an essential macronutrient for plant growth and development. Although the P-concentration in soil is 1000 folds higher than in plants, it is rarely available for plant uptake due to low diffusion and high fixation rate in soil. Hence, plants experience P-deficiency in the absence of P-fertilization, which may cause approximately a 30–40% decrease in crop yield. This highlights the importance of using a large amount of phosphate fertilizers to meet crop demands. As P-fertilizer is derived from a nonrenewable and finite source of rock phosphate, this resource is decreasing over time. In addition, farmers are applying P-fertilizers randomly without considering the soil stock, which leads to the loss of P-resources. The low P-use-efficiency (PUE) of plants in the field condition (15–20%) highlights that most of the soil-applied P remains unavailable to plants, and excess P causes ground and surface water contamination (i.e., eutrophication) through leaching and runoff, which ultimately results in environmental pollution. Therefore, it is crucial to apply P-fertilizers considering the soil test value and PUE to protect the environment from contamination and sustainable management of P-resources. This chapter mainly focuses on the sustainable management of P in agricultural fields for environmental conservation.

Keywords: plant phosphorus nutrition, phosphorus use efficiency, phosphorus fertilizers, environmental pollution, sustainable management

1. Introduction

Phosphorus (P) is an essential macronutrient for plant growth and development and is also considered as an important nonrenewable global resource for the agricultural production system [1]. It is an important growth-limiting factor in the agricultural production of the world due to its immobility and poor availability to plants in soil [2, 3]. Continuous application of P-fertilizer is crucial for the modern agricultural production system. A large amount of P-fertilizer is derived from the finite and nonrenewable source of phosphate rock. If this situation continues, it is predicted that the current global rock phosphate reserves could run out within the next 50–100 years [4, 5], or peak phosphorus could occur due to the global demand for agricultural production within a decade [5]. The fertilizer industry is concerned with the already rising cost of phosphate fertilizer associated with agricultural production. Because of this, scientific researchers are paying more attention to the long-term sustainable management of P-fertilizer. It is evident from different research findings that P is involved in several plant physiological and biochemical functions of plants. It is actively involved in growth and reproduction [6], flowering [7], seed formation [8], root development [9], disease resistance [10] and photosynthesis [11]. As a structural component of nucleic acids, lipids, and sugars within the plant cells, it is actively involved in the growth and development of plants both at the cellular and whole plant levels. The deficiency of P in the soil causes a significant decrease in primary root growth. It alters the root architecture (morphology, topology, and root distribution) by lateral root formation and increasing the length and density of root hairs [12]. Reduced root growth also causes a decrease in plant growth and results in significant crop loss. This highlights the importance of P-nutrition in crop production and emphasizes sustainable P-fertilization to enhance plant growth and development.

Phosphorus is a scarce and complicated element because it involves organic and inorganic (35–70% of total P in soil) stocks in soil [13]. P is one of the most important nonrenewable resources, and it has already received global attention due to its low availability in soil (mainly due to slow diffusion and high fixation in soil) [14]. Optimum P-fertilization is necessary to make an economic profit in farming, but the application of P-fertilizer to soils having excess P is not economically beneficial. If P is not applied to soil, plants take up P from soil reserves. In contrast, P applied to the low P soil might be profitable in farming [15]. Soils containing optimal amounts of P need to be properly managed, with appropriate fertilizer applications to maintain (or slightly decrease) their P-status. Adopting sustainable P-fertilizer management to reduce fertilizer costs would also decrease the negative effects of leaching and runoff to the environment.

Therefore, this chapter will focus on different aspects of P-management for sustainable environmental conservation. It will also review the biochemical functions, forms, behavior, and transport of P in soil. The problems associated with P-management strategies and possible action plans for sustainable agricultural and environmental conservation regarding the changing global perspectives are presented.

2. Biochemical and physiological functions of phosphorus

Phosphorus is a major essential nutrient element for plants that plays a crucial role in every developmental stage of life from very early to adult. This element improves crop yield and quality, and the functions of P cannot be performed by any other nutrient [14]. A plant can neither complete its normal reproductive process nor reach its highest yield potential without an adequate supply of P because this macronutrient has a major contribution to multiple cellular functions. As a structural component of nucleic acids, sugars, and lipids, P takes part in all the growth and developmental processes at both cellular and whole plant levels as, for example, cell division/elongation, membrane structure maintenance, enzyme activation, or inactivation, biomolecule synthesis, photosynthesis, respiration, high-energy molecules formation such carbohydrate metabolism, nitrogen fixation, seed germination, seedling establishment, root and shoot development, flower and seed formation, improves disease and stress resistance etc. (**Figure 1**).

Various biochemical functions of P are discussed in the following sections.

2.1 Structural component

The total P-concentration determines P compartmentalization within the plant cells. P makes up about 0.2% of a plant's dry weight [16, 17]. The optimum concentration for most of the crops is below 4.0 mg P g^{-1} dry weight [18–20]. Two forms of P function in plant tissues such as free inorganic orthophosphate form (Pi) and organic phosphate esters. Pi is metabolically active and is located in the cytoplasm. When P is excess, it is stored in the vacuole in esterified forms, and from this organelle P is supplied to cytoplasm on cellular demand. Nucleic acids, phospholipids, phosphorylated metabolites, and proteins are some of the esterified forms of P.

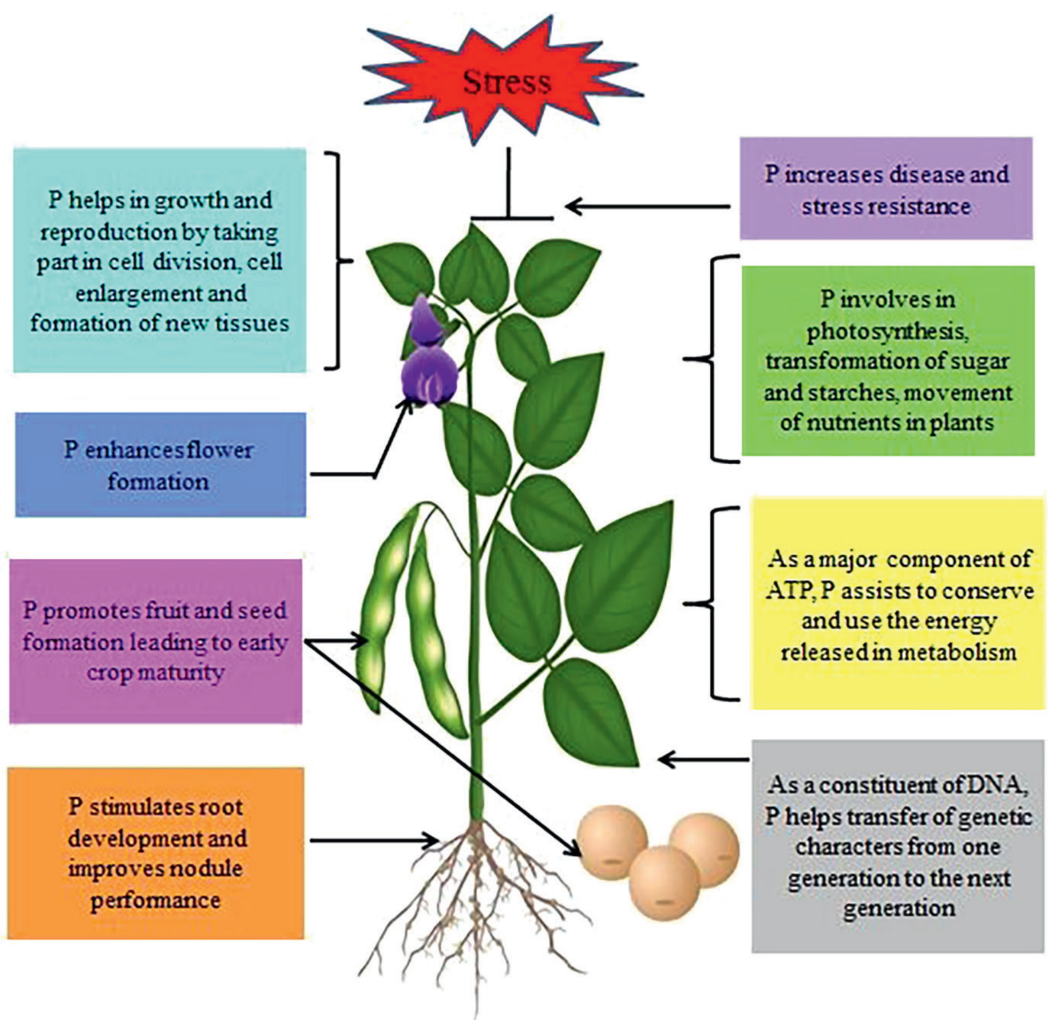

Figure 1.
Schematic representation of the major physiological and biochemical functions of phosphorus (P) in a typical legume plant. P has a significant contribution to photosynthesis, carbohydrate metabolism, energy release, transfer of nutrients and genetic materials, resistance to stresses and diseases, cell division and development, formation of plant organs such as flower, fruit, and seed, development of roots, nodules, etc., and thus being an indispensable element in plants life from germination up to maturity.

2.1.1 Sugar phosphates

Sugar phosphates, most of which are Pi esters of monosaccharides, are intermediate compounds of carbohydrate metabolism. Phosphorylation of carbohydrates followed by reaction with ATP forms sugar phosphates, some of which include phytic acid, glucose-6-phosphate, and dihydroxyacetone phosphate. As constituents of glycolysis and respiratory reactions, these phosphorylated compounds play significant roles in photosynthesis as well as the synthesis and breakdown of carbohydrates.

2.1.2 Phospholipids

Phospholipids play a pivotal role in the structural regulation and dynamics of the cytoskeletal organization by the interaction of its molecules with multiple actin-binding proteins, viz. profilin, gelsolin, α-actin, cofilin, filamin, vinculin, etc. [21, 22]. Phospholipid molecules are considered as essential structural elements of cell membranes, emerging as important second messengers to regulate plant growth, development, and cellular responses to environmental stresses through different mechanisms [23]. It is well recognized that phosphoinositides are involved in membrane trafficking and signaling in the cell responses to stress stimuli such as salt, osmotic, temperature, pathogen stressors, etc. [23, 24].

2.1.3 Nucleic acids

As a major component of nucleic acids, P is involved in the transfer of genetic materials needed for growth and development from one generation to the succeeding generation. Nucleic acids are polynucleotides that consist of nitrogen-containing aromatic bases attached to a pentose sugar, connected with a phosphate group. DNA and RNA are the two principal classes of nucleic acids that form the largest organic P pool in plants, ranging from 0.3 to 2.0 mg P g^{-1} dry weight in various crops [25]. Both nucleic acids direct the process of new protein synthesis such as enzymes and determine the inherited traits in living organisms including plants.

2.2 Energy and electron transport

The role of P in cellular metabolism, mainly energy transport, is of great significance. P is involved in various cellular processes because it is linked with high-energy bonds, and the high-energy P-containing compounds such as phosphoanhydride, acyl phosphate, enol phosphate, etc., transfer energy to acceptor molecules. The phosphates are formed at the sites of energy production and are donated to other molecules at sites of energy consumption. The most common P energy currency is found in ATP, whose hydrolysis releases a great amount of free energy required for multiple cellular processes like macromolecule synthesis, membrane phospholipid formation, nutrient transport, etc. For example, α, β, and γ-phosphate release energy of 13.8, 27.2, and 34.0 kJ mol^{-1}, respectively, after hydrolysis [25]. Similarly, phosphoanhydride bonds are found in di- and triphosphate molecules in guanine, cytosine, uracil, and thymine nucleosides. In gluconeogenesis and saccharide metabolism, guanosine triphosphate (GTP) and uridine triphosphate (UTP) are important electron donors. Phosphorus is an essential part of the structure of triphosphopyridine nucleotide (TPN) that provides a similar transportation function in plants as adenosine diphosphate (ADP) and adenosine triphosphate (ATP). These nucleotides function as carriers of electrons or hydrogen between sites of oxidation and reduction reactions occurring in photosynthesis and respiration.

2.3 Photosynthesis

Phosphorus directly or indirectly regulates the photosynthesis process as a primary substrate, utilizing light energy to form sugars and a three-phosphate-containing molecule ATP in the presence of chlorophyll, CO_2, and water. It should be noted that ATP is the key driver of different metabolic reactions in plant cells that is required for the development of structural and storage components. P is a prime element of the thylakoid membrane and is crucial for the regulation of photosynthetic machinery, viz. PSI, PSII, LHCP, cyt-f, cyt-b, and antenna mobility, as reported by Rychter and Rao [26]. In fact, apoprotein phosphorylation of antenna is a vital step in photosynthesis. Various processes involved in photosynthesis depend largely on the availability of Pi, which is controlled by an increase in photorespiration. Alterations in Pi availability in cytoplasm modulate the activation of multiple enzymes (such as RuBisCO, sedoheptulose-1,7-bisphosphatase, and fructose-1,6-bisphosphatase) and amounts of intermediates of the photosynthetic carbon reduction cycle. Besides, Pi possesses a great role in the partitioning of the photosynthates in various plant tissues and the distribution of newly fixed C between chloroplasts and cytoplasm during starch and sucrose synthesis, respectively.

2.4 Glycolysis

Phosphorus is involved in every reaction of the glycolysis process in plants. In the initial reactions of glycolysis, energy from ATP is necessary. However, in the subsequent reactions, ATP is generated with a net release of energy. Actually, ATP is the energy end product of glycolysis, which is the predominant pathway of carbohydrate metabolism in plant tissue. Pentose phosphate pathway is one of the major aerobic processes of carbohydrate degradation and synthesis where a series of oxidation-reduction reactions begin with five carbon sugars having a phosphate molecule attached to them. The activities of several glycolytic enzymes phosphofructokinase (PFK), nicotinamide adenine dinucleotide (NAD)-glyceraldehyde 3phosphate dehydrogenase (G3PDH), 3-Phosphoglyceric acid (3-PGA) kinase, and pyruvate kinase (PK) depend on the concentration of adenylate and Pi. The levels of respiratory intermediates, viz. hexose phosphates and 3-phosphoglyceric acid (PGA), reduce during P-deficiency. The activities of PFP and nonphosphorylating NAD-G3P-DH, phosphoenolpyruvate (PEP) carboxylase, and PEP phosphatase have been found to increase under P-deprived conditions.

2.5 Nutrient transport

Plant roots extract nutrients from soil solution and translocate them within the body, and most of this movement depends on a transport system through the cell membrane that requires energy to override the opposing force of osmotic equilibrium, which is provided by ATP through its high-energy phosphate bonds. ATP or some other phosphorylated compounds conduct the transport of nutrients through membranes of plant organs such as roots and leaves by an energy-driven process.

Several plasma membrane-bound transport proteins play vital roles in nutrient transport, and for example, proton pump named H^+-ATPase imports nutrients into the plant together with the export of H^+ by utilizing ATP [27]. Therefore, to enable nutrient transport smoothly with the use of ATP, these membrane proteins are abundant in the epidermal and endodermal root cells, xylem and phloem cells [28–30].

2.6 Nitrogen fixation

Phosphorus assists in enhancing rhizobial bacterial population in soil. It is considered as a principal plant nutrient that is strongly involved in biological nitrogen fixation and nodule performance in legumes. *Rhizobium* bacteria require energy for growth, reproduction, and functioning, which is provided by ATP that is transformed into ADP with concurrent liberation of inorganic phosphate. For each molecule of N_2 reduction for fixation, at least 16 molecules of ATP are hydrolyzed, showing that N-fixation is an energy-demanding process. Nodule formation and development are largely inhibited in P deficit condition, and as a result, nitrogen fixation is greatly impaired. Nitrogenase enzyme activity is also positively correlated with plants P nutritional status. Researchers found higher root nodule biomass in pea plants with higher supply of P [31] and lower concentration of ATP and energy charge in soybean nodules with a low P supply [32].

2.7 Seed germination

The embryo in plant seeds requires P for growth and development until the formation of a root system. For seed germination and seedling vigor, the seed P-content is a vital factor because seed P is the only P available to plants during germination that aids in nutrition and faster establishment of young seedlings. With the rise of P-concentration in seed, dry matter production of seedlings of annual plants increases. P quantity in seeds of plants differs from about 0.15 to 0.60% in seeds of wheat, oats, barley, and lupins and from 0.30 to 1.10% in those of subterranean clover and annual medics [33]. Conversely, according to some recent studies [34, 35], a lower concentration of seed P exerted no difference in seedling vigor, plant biomass, and yield in comparison with a high concentration of seed P, suggesting that an optimum concentration of seed P is adequate for seed germination whereas, higher P-concentration in seeds might be useless.

2.8 Root and shoot growth

Phosphorus is inextricably involved in plant growth from cellular to whole plant level, playing a significant role in cell division and cell enlargement that are crucial for root and shoot development. It stimulates root development required for the plant to get nutrients and support from the soil. Phosphorus is essential for better growth parameters of plants such as height, biomass of shoot, area and number of leaves, and timely appearance and development of tillers in cereals [36]. The deficiency of P can lead to limited cell divisions and enlargement in leaves, resulting in reduced shoot biomass. Plant growth is considered to be more sensitive to P-availability compared to photosynthesis [37]. Under long-term Pi-deficient conditions, the relative growth rate decreases as a result of reduced ATP concentration in roots [38]. Limited leaf expansion under low P-supply might be due to low turgor pressure for leaf expansion resulting from decreased water transport in the leaf from the growth medium.

2.9 Flower, fruit, and seed formation

Phosphorus is responsible for the reproductive development of plants such as formation of flower, fruits, and seeds as well as crop maturity at the right time. P-deficient plants take longer period to mature and bear few fruits and seeds with poor quality. Phosphorus nutrition can regulate anthocyanin production in leaves flower stalks by modulating the activities of phenylalanine ammonia-lyase (PAL) and chalconeisomerase (CHI) and epidermal pH values [39]. Optimum amount of P in soil ensures a higher number, dry matter, and yield of fruits and seeds with a greater harvest index. For development and maturation, both fruits and seeds require large quantities of P, and an inadequate supply of P can reduce the size, number, viability, and quality of seeds. In cereal crops such as rice, wheat, and maize, the majority of total P (about 75%) is stored as phytin or associated compounds, whereas 4–9% is stored as inorganic phosphate and 15–25% as cellular-P [40].

2.10 Disease and stress resistance

Phosphorus is crucial for the general health and vigor of plants, and it enhances resistance and tolerance to stress and diseases, which otherwise can reduce crop quality and production. P-balancing with other nutrient inputs is of prime importance to decline the risk of disease infection. In a complete and balanced fertility program, P is a major element that can improve crop health to withstand stress and to become less susceptible to disease occurrence. However, the role of P in disease resistance is variable and inconsistent [41].

3. Forms of phosphorus in soil

The total P in soil is a combination of both inorganic and organic forms. Generally, the inorganic P is higher than the organic P because it accounts for around 50–85% of soil total P [42]. The inorganic P constitutes some active forms of P like calcium P (Ca-P), iron P (Fe-P), and aluminum P (Al-P) and inactive forms like occluded P, reductant soluble P, and residual P [43, 44]. The concentration of total P ranges from 50 to 3000 ppm in soils, but it has little contribution to the bioavailability of P in soils [45]. The solution P, which meets the plant's requirement, is available in very low concentrations (around 0.05 ppm) in soil [46].

Organic P consists of inositol phosphates, phospholipids, and nucleic acids. Inositol phosphates exist as a dominant pool of organic P in soil because the other two forms are highly susceptible to microbial degradation [47]. Globally, the share of organic P in total soil P is observed between 1 and 30% [48, 49]. In Indian soils, this share varied from 10 to 50% [50]. However, the contribution of organic P may increase up to 80% in forest and grassland ecosystems [51].

4. Behavior and chemistry of phosphorus in soil

When P-fertilizers are applied to the soil, they react with cations (Ca, Fe, and Al) and form insoluble P-compounds. Consequently, P-use-efficiency declines, and crops can recover only 15–20% of applied P [52]. In mineral soils, P is highly immobile [53]. P-cycling in soil occurs through numerous processes, viz., mineralization-immobilization, precipitation, adsorption-desorption, dissolution, and plant uptake [46, 54]. The fixation of P is common in acid soils because P precipitates as oxides and hydrous oxides of Fe and Al or gets adsorbed on clay surface or surface of oxides and hydrous oxides of Fe and Al [55, 56]. Similarly, in calcareous soils, these phenomena (precipitation and adsorption) lead to the formation of insoluble Ca compounds [57, 58]. The adsorption process takes place by ligand exchange, which favors monodentate phosphate complexation [54, 59]. Based on adsorption, P-forms can be classified as labile and nonlabile [60]. Labile forms are related to weak adsorption because of low desorption time. They supply P to the soil solution. Thus, under equilibrium conditions, P-dynamics in the soil [54] are represented as:

$$\text{Nonlabile P} \leftrightarrow \text{Labile P} \leftrightarrow \text{solution P}. \quad (1)$$

In the mineralization process, the soil organic P is converted into inorganic P by the microbes present in the soil. This is also known as P solubilization. Organic P hydrolysis is performed by microbes producing enzymes (phosphatase, phytase) and organic acids (formic, oxalic) [61]. When the available P is low in the soil, microbial immobilization of P begins, i.e., inorganic P gets transformed into organic P [62].

With the increase in soil age, the concentration of nonlabile forms of P increases [44]. P-availability in soil is dependent upon pH, organic matter, clay content and/or type, moisture content, temperature, aeration, and other properties of the soil. In heavily P-fertilized soils of northern Iran, the reported higher P-adsorption was argued due to the high content of clay and Fe and Al oxides [43]. The capacity of soils to supply this nutrient to plants or the buffering capacity of soils is determined by quantity and intensity factors [63]. This is determined by sorption and desorption curves. Quantity is the solid phase that equilibrates with the solution and can also represent the buffering capacity of soils to meet the P requirement of plants [64]. Therefore, to improve the efficacy of P-fertilizer recommendations, buffering indices must be considered in our soil testing programs to know about P-uptake at different stages of plant growth [65]. The release of P occurs in simultaneous processes, viz., desorption at a higher rate and diffusion at a slower rate [66].

The availability of P increases with the addition of organic matter. As through mineralization of organic matter, the available form of phosphorus is released to soils. Retention of P reduces because phosphate absorbed into soil competes with organic molecules. In soils with high clay contents, the retention capacity of phosphorus will be high because the surface area per unit volume is very high of clay particles that absorb phosphorus very easily. On the other hand, the adsorption capacity of P increases when soils have a sufficient amount of minerals. The mineral composition of the soil influences the phosphorus adsorption capacity. The availability of P will be higher in soils that have 6–7 pH. At low soil pH, the Fe and Al make strong bonds with phosphorus, and phosphate tends to precipitate with calcium at high soil pH. Another factor also affects the availability of phosphorus to plants; like in cool weather, the organic matter takes a long time to decompose compared with warm and hot weather.

5. Phosphorus transport and contamination in the environment

Agricultural land is the major source of P-transport in surface waters. The loss of P as runoff causes P enrichment or eutrophication in aquatic ecosystems.

Therefore, agricultural management practices should focus on reducing P-transport caused by excessive consumption of inorganic fertilizers and organic manures [67]. Both soil and hydrological factors are responsible for the movements of P [68]. The former decides the initial transport, while the latter is associated with transport as well as the pathways. There are three major pathways by which P is transported to surface water bodies. Those are surface runoff, subsurface flow, and vertical flow [67]. Minimizing soluble P concentrations or increasing water infiltration in soil for P-adsorption will help in decreasing the dissolved P-transport [69]. The subsurface flow of P is a concern only for soils having high P-saturation or preferential flow. At high rainfall intensity (hydrological factor), fertilizers containing a higher concentration of water-soluble P can increase P-transport in runoff [70]. Manures containing high organic P (like poultry manure) may contribute to dissolved P-losses via leaching and displacement of loosely bound inorganic P [71, 72]. The possible transport of P in the environment has been highlighted in **Table 1**.

Long-term application of P-fertilizers (like triple superphosphate)may increase the concentrations of some trace elements or heavy metals (arsenic, cadmium, copper, chromium, nickel, vanadium, and zinc) in soil [73]. Mining and processing of rock phosphate cause significant contamination (from radioactive to heavy metal pollutants) in the environment [74, 75]. Phosphogypsum, a by-product obtained during the processing of rock phosphate, marks a serious potential hazard for human health and soils, water, and atmospheric pollution [75]. The use of organic wastes (pig slurry and cattle slurry) above crop P demands saturates soil adsorption sites, leading to P-migration in the soil profile and subsurface water contamination [76]. Therefore, instead of the bulk application of the bioresources, technologies should be framed to recover P from human and animal wastes including sewage, sludge, manure, incineration ashes, etc., by developing contaminant-free fertilizers, e.g., struvite (ammonium magnesium phosphate) and/or other soluble products for efficient P-cycling [77].

P-sources	Anthropogenically contribution per day	Contribution percent of total P (%)
Kitchen waste disposal	0.1	4
Toilet	1.6	59
Bath, sinks, and machines	1	37
Total phosphorus (P)	2.7	—
Water body	**Water body type**	**% Total P load from septic systems**
Cottonwood Lake	Freshwater lake	4
Lake Carlton	Freshwater lake	14
Pine View Reservoir	Reservoir	20
Pend Oreille Lake	Freshwater lake	25
Ontario Lakes	Freshwater lake	55
Otsego Lake	Freshwater lake	20

Table 1.
Transport of phosphorus (P) in the environment.

6. Importance of assessing phosphorus use efficiency

Using phosphorus efficiently means that the phosphorus taken up by plant per unit produces yield or biomass [78] and is distinguished when relevant by using subscripts, PUEt and PUEy, respectively. Phosphorus use efficiency may improve through strong agronomic practices, like the calculated amount of fertilizers, suitable timing, right place, and right crops. Mostly, the biomass for any plant is taken from the above-ground parts. There are so many limitations to reserves rock phosphate globally, and awareness is increasing. These reserves are used to increase or maintain the present agricultural productivity and produce crops [5]. Around 57% of the annual grain crops like pulses, cereals, and oil seeds cover the dietary energy for the present world's rapid growing population [79].

The primary goal of testing soils for P is to identify the supplementary P needed to prevent crop losses due to P-deficiency. Plant-available phosphorus in soil can be estimated using a soil test that offers an index of plant-available P. Second, soil testing for P is used to track the amount of accessible P in the soil. For evaluating fertilization procedures and the selection of waste disposal options, this data can be valuable.

A wide variety of chemical forms of P can be found in soil. All of these factors influence the plant-available pool to variable degrees. The amount of plant-available P in a given soil is not a fixed figure. According to a variety of soil and plant root properties and the environment, this can vary. A soil's plant-available P-content can be challenging to forecast. However, some effective P extraction methods have been established, which correlate well with P-uptake in controlled conditions. Routine soil fertility tests typically refer to a relatively rapid nutrient extraction, which results in an accessible soil nutrient value connected with crop response to fertilization. It is usual to practice to employ Mehlich-1 (M1) and Mehlich-3 (M3) for fertilizer P and K rate recommendations. There may be some variations in fertilizer rate recommendations even if the numerical soil test findings are the same, even if soil testing laboratories utilize equivalent extraction and quality control techniques and comparable instruments [80–82].

Soil testing relies heavily on developing standardized techniques (extract and analytical methodologies), test interpretation, and nutrient recommendations, all of which are based on field calibration and validation.

The following documents contain extensive information on soil testing, soil test extractant, and the correlation and calibration processes, as well as fertilizer recommendation regulations:

1. First, we need to understand what soil testing for plant-available nutrients means and why we use it in the first place. To put it another way:

2. Processes for the Correlation and Calibration of a Soil Test Extractant (SL 409).

3. Recommendation Philosophies for the use of fertilizer (SL410).

4. Extracting Nutrients from Acid-Mineral Soils of Florida using Mehlich-3 Reagent (SL 407).

Test results for specific soil features and P-availability are affected by some different soil parameters. If you understand the basic chemistry behind extractant-soil mixture, you can predict some of these traits. The effects of other properties on soil test results are more modest.

There is a perception that carbonates in soils pose a barrier to robust acid extraction procedures like Bray and Kurtz or Mehlich I. The Bray PI test for calcareous soils is lower than the $NaHCO_3$ test [83]. $CaCO_3$ neutralizes the acid, releasing Ca, which precipitates the fluoride. This reduction has largely been attributed to this process. Thus, the ability of the extractant to remove P is diminished. However, the Bray PI and $NaHCO_3$ tests have been performed equally on calcareous soils in Colorado and Nebraska in other correlation investigations [84]. As a result, factors other than the total $CaCO_3$ level may be involved in deciding whether the acid tests are unsuccessful. The use of acid tests on calcareous soils is generally avoided because of these additional unknown issues. Soil-to-solution ratios of 1:100 or 1:100 have enhanced correlations on neutral and calcareous soils and appear to alleviate the problem of soil toxicity [85–87].

The pH of noncalcareous soils has been identified as another factor influencing soil test performance, although not consistently. A field study in British Columbia showed that correlations were higher for alkaline soils than acid soils for both Bray PI and $NaHCO_3$ tests [88]. A South Dakota study showed that correlations were lowest in the pH range of 6.6–7.0 for both tests [86]. An Ohio study demonstrated only slight reductions in correlations when the pH exceeded 5.5 for Bray PI and $NaHCO_3$ tests [89].

7. Effect of soil properties on phosphorus use efficiency (or phosphorus dynamics)

The efficiency of P-use depends mostly on the complex interactions among the physical, chemical and biological characteristics of soils, and the processes involved with these properties. These properties can directly influence root growth and development, restricting P-uptake. Soil depth, structure, stoniness, moisture retention, and composition of the soil atmosphere can influence P-dynamics. Notably, the prevailing soil properties such as soil texture, mineralogical composition, total surface area, pH, $CaCO_3$ content, organic matter content, the presence of Fe and Al-hydroxides, etc., can considerably alter the solubility, availability, and extractability of P in soil [90]. Due to the presence of dense subsurface layers (e.g., plow pans) and surface-soil compaction, the diffusion of phosphate ions in soil is decreased, and root growth and development are hindered. Although the slow movement of P by diffusion is usually attributed to the tortuosity of the pore system, the reactive sites for P-adsorption on soil minerals around the pores can hold phosphate ions, temporarily or permanently, that slow or prevent their movement along the pore [91]. Soil texture influences the chemical behavior and hydrology of soils and affects the formation of Al-organic bonded stable P and leaching of P from soils [92, 93]. By practicing zero-tillage, cultivating permanent crops, and maintaining a crop-residue cover, and by minimizing traffic over the soil surface and reducing invasion of livestock in wet and heavy-textured soils in humid temperate regions, the physical limitations of P-uptake can be controlled to some extent. Besides, soil-borne fungal pathogens and nematodes injure plant roots and limit P-uptake and to overcome this problem, crop rotation is a suitable option.

Soil acidity is a chemical limitation to the efficient use of P-fertilizers as it has adverse effects on P-uptake. Soil pH regulates the release of Al from various clay minerals and the dissolution of Al hydroxy compounds in soil. At low pH with high Al-concentrations in the soil solution, root tips and lateral roots are thickened and turn brown, causing the reduction in P-uptake. As a result, P translocation in the upper parts of the plant decreases, and P metabolism is hampered. These problems can be ameliorated by adding lime and other acid-neutralizing materials that can increase pH as well as base saturation percentage. P-distribution in different soil P pools is an inherent soil property, and changes in the P-distribution in the pools are difficult to achieve. Scientists around the globe investigated the impact of pH change by adding lime to acid soils on retention and extractability of P and found no consistent influence on soil P availability [94–97]. The amount of readily available plant P increases with the increase of organic matter in the soil [98]. In P-deficient soils, applying a material that can compete with the phosphate ion for the adsorption sites within the soil such as silica or silicate might be a suitable option to increase P-availability [99].

8. Modeling phosphorus transport to water bodies and phosphorus index

According to the conceptual model and hillslope hydrology, it is vital to identify significant source locations, which are areas with disproportionately high P-losses, to efficiently manage P-movement regularly at the field and watershed scales. Soil and water assessment tools like the Soil and Water Assessment Tool [100] have been developed to identify critical source locations of P-migration (SWAT).

While various developments in modeling, including graphical user interfaces and geographic information system (GIS) layers, have been made in the field, the fundamental methodologies to modeling P-movement have remained essentially unchanged [101]. Land use, soil texture, and topography are the primary inputs for most P-transport models, but other factors like management techniques are also widely used as data. There are three preliminary modeling approaches: processed-based, export-coefficient, and statistical models [102].

For the original P-index, Lemunyon and Gilbert [103] set out to assess the risk of P-transport to water bodies, identify the essential components that drive P-loss, and assist in selecting management measures that reduce P-loss. It has evolved significantly since its introduction in 1993 [103] from being a critical source area identification to now serving as best management practice selectors in manure application scheduling tools, manure application rate calculators, and regulatory mechanisms of some states in the United States of America [104]. In the United States and Europe, P-indices have included as many as 34 variables from each location [105]. Runoff class, soil erosion, irrigation erosion, soil P-test, and P-fertilizer application rate and technique, organic P-source application rate, and method of organic P-source application were the initial eight parameters to evaluate in the original P-index, which was updated in 2010.

Some site factors may be more important than others in influencing P-migration from the site. The weighting factor for each site attribute was determined by professional judgment and historical experience. To get a weighted score for a site characteristic, the P-loss rating value is first multiplied by the site characteristic weighing factor. P-loss is less likely in fields with low P-indices, while P-loss is more likely in areas with high P-indices.

9. Global phosphorus consumption

Due to the growing world population and increasing demand for food consumption, the growing demand for bioenergy crops will affect the future P-use particularly

Year	Diet	P-consumption (kg/capita/y)		Total global P-consumption (Mt)	Fertilizer P-use (Mt)
		Developed countries	Developing countries		
2003	Current	0.64	0.43	3	16.24
2020	Current	0.64	0.43	3.6	19.4
	Affluent	0.64	0.64	4.9	26.7
2050	Current	0.64	0.43	4.2	22.8
	Affluent	0.64	0.64	5.9	31.8

Source: Smit et al. [107].

Table 2.
Global anticipated phosphorus (P) consumption.

when grown on additional marginal land with low P-status. From 1961 to 2013, total global P-consumption has increased fivefold to 31 million metric tons [106]. For 2050, with a global population of 9 billion, P-demand would rise by 40 and 96% for current and affluent diets, respectively [107]. **Table 2** shows the anticipated global P-consumption in developed and developing countries.

In 2020, China was the country with the largest consumption of phosphate fertilizers, with more than 11 million metric tons, which was followed by India and Brazil, with 8.98 and 6.04 million metric tons, respectively [108]. That year, ammonium phosphate was the most consumed phosphate fertilizer (over 25 million metric tons of P_2O_5) worldwide, followed by complex nitrogen, phosphorus, potassium (NPK) fertilizers (over 12 million metric tons of P_2O_5), as reported by Statista [109]. World consumption of P_2O_5 contained in fertilizer products increased by 7% in crop year 2021 compared with that in crop year 2020 [110]. The increases in world consumption and trade were driven by high crop prices, increased planted crop areas, and increased crop exports. This was a continuation of the trend that began late in 2020, as markets rebounded from poor weather conditions in the growing season. South America and Asia were leading regions of growth in consumption of phosphate fertilizer in terms of percentage increase over that in 2020. With the continuous rise in P-consumption, it is necessary to develop a system approach for addressing P supply, demand, and loss.

10. Management strategies for phosphorus to protect the environment

10.1 Phosphorus in the soil

Apatite and other primary minerals are the principal sources of P in the environment (calcium phosphate). Many rocks and soils include phosphate-bearing minerals. It takes time for these minerals to break down and release phosphorus into the soil. P is a highly reactive substance in the environment. This orthophosphate exists in a variety of different phosphate forms in solution, depending on the acidity. In the absence of rapid uptake by plants or soil micro-organisms, orthophosphate is likely to recombine with other soil chemicals (e.g., calcium, iron, aluminum, and manganese). As a result, P has long been regarded as the most important agricultural nutrient.

10.2 Phosphorus in the agriculture

Commercial, inorganic, phosphate fertilizers have been used to correct soil P-deficiency over the past 50 years. Plants can benefit from phosphate fertilizers because they are made by removing P from phosphate-rich rocks and making them more accessible. P has built up in agricultural soils due to massive volumes of these fertilizers over many decades. Crop yields are not adversely affected by soils with high P-reserves, except for the availability of micronutrients such as zinc. Before the 1970s, the practice of using high-phosphate fertilizers to increase soil phosphorus reserves was encouraged, and it was equated to "saving money in the bank." According to conventional belief, having high soil P-levels was equivalent to having significant cash in the bank. As a result of growing worries about the association between high soil P levels and the harm to water quality posed by P-rich soil particles entering the water through runoff, this concept has come under scrutiny in recent years.

10.3 Controlling runoff in case of agricultural phosphorus

Phosphate fertilizers, plant waste, manure, and agricultural effluent should not be directly applied to surface waters to prevent point source P-contamination. Pollution caused by nonpoint P-sources such as agricultural fields can be reduced by regulating the amount and kind of runoff. To avoid P pollution from surface waters, areas with steep slope and highly erodible soils close to surface waters should be avoided. A site's risk of becoming a prospective polluter can be considerably affected by management approaches. Sediment can be reduced significantly with the use of cover crops and buffer strips. Another factor that can enhance the risk of contamination is a lack of soil cover or barriers between a farm and its water.

Generally, water erosion happens on slopes, and the intensity of the decline increases with the slope's degree. Using no-till farming can reduce soil erosion. Additionally, crop residues can be left on the soil surface after harvest, and winter cover crops can be planted in the fall. Reduced water erosion can be achieved through the use of contoured tillage. Rather than going up and down the slope, plows are used to plow across it. The geometry of some fields makes this technique ineffective. To decrease water erosion, terraces can also be built. Soil erosion can be reduced by leaving agricultural remains on the field after harvesting. Leaving corn stalks on the field after harvest is one example of how crop residues can protect the soil from eroding throughout the winter. The residues protect the soil surface until the land is plowed, reducing the time it is exposed to the weather.

Protecting the soil from erosion during noncrop months is done by planting cover crops, such as grasses, legumes, or small grains. Once the main crop is planted, they remain in the field. Phosphorus levels in rivers and streams are reduced by cover crops, which reduce erosion. Cover crops can also take up P and other nutrients while other crops are not growing. Wildlife can also benefit from cover crops, which give food and shelter.

10.4 Management of fertilizer phosphorus sources

In agricultural runoff, the most prevalent sources of P are manure and compost, as well as mineral fertilizers [111]. Practices that can reduce the risk of agricultural land contamination with P include limiting the amount, timing, and method of application of P-fertilizer sources. There is a strong correlation between soil test P-levels (especially in newly fertilized plots, when the amount of soluble P in the fertilizer source is predominantly responsible for the dissolved P in surface runoff), with P-rate, and the timing of application, according to Mullins et al. [112]. Runoff water from fields getting broadcast P-fertilizer was shown to have a higher concentration of dissolved P than runoff water from locations where comparable quantities of P were absorbed 5 cm below the soil surface. All factors that enhance the danger of fertilizer loss, such as high fertilizer application rates and high rainfall regions, can be mitigated [113].

Additionally, some regions (e.g., areas with a lot of rainfall) should use less water-soluble fertilizers to decrease the transfer of P in runoff water [114]. When limiting incidental P-losses from fertilizer applications, scheduling the fertilizer P applications to correspond with dry weather is critical, especially in places with a lot of rainfall or regular irrigation [113]. Avoiding solid storms, which account for a significant portion of annual runoff P-loss, would prevent runoff P-loss. It has been found that delaying the application of P-nutrition sources until after a rainfall or runoff event reduces

Management strategies	**Agroecosystems**	**Effect on phosphorus transfer/losses**	**Causes/mechanisms**	**References**
Soil application of organic wastes like pig slurry and cattle slurry	Maize under no-tillage systems, subtropical environment	Increased P transfer by surface runoff	Addition of higher amounts of P in soil and the doses of organic wastes were fixed according to N requirement of crops	Lourenzi et al. [76]
Selection of crop genotypes with shallow root growth	Common bean under low-input systems	Reduced P-losses in erosion (sediment)	Greater P-uptake and shoot growth	Henry et al. [121]
Application of NPK fertilizers and organic amendments like farmyard manure, green manure, and paddy straw	Rice-wheat cropping systems	Reduced P runoff	Protection of aggregated P by consolidation of micro aggregates into macro aggregates	Mitran et al. [122]
Reductions in fall-applied N and P-fertilizer inputs	Winter wheat-maize systems	Reduced P-transport in agricultural watersheds	Decreased winter wheat and increased corn production	Lerch et al. [123]
Reduced tillage and green manure	Wheat under Mediterranean rainfed systems	Reductions in P-losses 64%	Low mobilization of soil particles	Martínez-Mena et al. [124]
Low application of poultry manure combined with high N/P nutrient sources, high N fertilizers, and N-fixation from cover crops	Grain-tomato rotations	Low P leaching risks	Increased P sorption	Maltais-Landry et al. [125]
Magnesium-salt-coated biochar	Cereals under organic systems	Reduced P leaching	P-adsorption capacity of biochar layer	Riddle et al. [126]

Management strategies	Agroecosystems	Effect on phosphorus transfer/losses	Causes/mechanisms	References
No-tillage and unincorporated manure	Maize	Reduced P loads in runoff	Increased infiltration and decreased sediment losses	Bundy et al. [127]
Chicken manure biochar	Wheat	Decreased P leaching	Increased plant P-uptake due to an increase in soil pH and mycorrhizal colonization	Madiba et al. [128]
Gypsum	—	Decreased P leaching	Increased calcium content in soil	Favaretto et al. [129]

Table 3.
Selected reports on the management of phosphorus (P) in agroecosystems.

the amount of P that makes its way into runoff [115]. When it comes to runoff, the number of rainstorms following application can affect the concentration of nutrients more than the amount of runoff or rainfall that occurs each year, according to [114].

When managing P for environmental protection, the ultimate goal is to avoid the transportation of P-sources. According to this perspective, preventive and intercepting procedures have been developed by Sharpley et al. [116] to reduce P-transport. There are two distinct approaches to dealing with P pollution: preventive measures like cover crops and interception technology like buffer strips meant to remove P from the landscape [117]. In addition to conservation tillage and crop-residue management measures, buffer strips and terracing have been advocated to reduce P-movement through erosion and runoff. Cover crops, grassed waterways, and the development of riparian zones have also been proposed [118–120]. In **Table 3**, we have presented different management strategies that can reduce the P-losses from agricultural soils.

11. Conclusion and future perspectives

In conclusion, P deficiency in agricultural fields due to high soil fixation and limited nonrenewable P-stock are the major concerns for researchers globally. The active involvement of P in several physiological and biochemical functions has been well-documented in various studies. Limited P-availability in soil affects overall plant growth due to the decrease in P-uptake by plant roots. Application of P-containing fertilizers supplements the P-demand, but random application causes contamination of surface bodies. Applying P-fertilizers considering the soil test value and PUE can contribute to the sustainable management of P and mitigate environmental contaminations. Future research trials should focus on improving the understanding of P-uptake, -utilization, and -transport mechanisms under low P-environment. Further, extensive research is required in the field of root biology, along with identifying and enhancing gene expression for improved P-acquisition and use efficiencies.

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