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Phosphorus Dynamics in Terrestrial and Aquatic Ecosystems: Processes, Challenges and Management Perspectives

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Phosphorus (P) is a fundamental macronutrient that regulates primary productivity, biodiversity and ecosystem sustainability. Unlike nitrogen and carbon, phosphorus has no significant gaseous phase and its cycling is therefore primarily controlled by geochemical and biological processes within the lithosphere, pedosphere and hydrosphere. In terrestrial ecosystems, P dynamics are strongly influenced by soil mineralogy, sorption–desorption reactions, organic matter decomposition, microbial transformations and land-use practices. High soil fixation limits its bioavailability, while agricultural intensification has created nutrient imbalances and low phosphorus use efficiency. Conversely, in aquatic ecosystems, phosphorus governs trophic status and is a central driver of eutrophication. Inputs from agricultural runoff, wastewater and atmospheric deposition, combined with internal loading from sediments, enhance dissolved inorganic phosphorus (DIP) availability, often leading to algal blooms and hypoxia.

Despite its importance, phosphorus management poses significant challenges. Global phosphate rock reserves are finite and unevenly distributed, raising concerns over long-term food security. Furthermore, anthropogenic activities have accelerated P fluxes beyond natural thresholds, contributing to water quality deterioration and ecosystem degradation. Balancing agricultural productivity with environmental sustainability requires innovative management approaches. Emerging strategies include precision fertilization to match crop demand, use of P-efficient crop genotypes, microbial inoculants that mobilize insoluble P and recovery of phosphorus from wastes such as manure, sewage sludge and food residues.

Understanding phosphorus dynamics across terrestrial and aquatic systems is therefore essential for developing integrated nutrient management frameworks. By linking biogeochemical processes with socio-ecological challenges, sustainable phosphorus management can reduce environmental risks, enhance resource-use efficiency and secure future food production. This review article will explore the fundamental processes regulating phosphorus cycling, highlight key challenges in both terrestrial and aquatic ecosystems and discuss potential management perspectives that integrate ecological and agricultural sustainability.

Keywords: Aquatic ecosystems; phosphorus; terrestrial; algal blooms and hypoxia.

1. INTRODUCTION

Phosphorus (P) was first discovered in 1669 by the German alchemist Hennig Brandt. Its name originates from the Greek words *phos* (light) and *phorus* (bearer), reflecting the element's luminescent properties when first isolated (Blaise et al*.,* 2018). Phosphorus is the 11th most abundant element in the Earth's crust, averaging about 1,200 mg P kg^{-1}, with typical soil concentrations ranging between 200–800 mg kg^{-1} (Tiessen, 2008), yet it contributes crop production, food security and water quality.

Phosphorus is a vital macronutrient for plant and microbial growth, playing a crucial role in many physiological and biochemical processes. It is a fundamental structural component of nucleic acids, co-enzymes, phospholipids, phosphoproteins and cellular membranes. It also serves as an energy currency in the form of ADP and ATP, regulating a wide range of metabolic processes (Vance et al*.,* 2003; Rodolfo et al*.,* 2021). P supports critical functions such as photosynthesis, respiration, glycolysis, signal transduction, redox reactions, lipid metabolism, carbohydrate transport and the maintenance of osmotic potential (Plaxton and Tran, 2011).

The dynamics of phosphorus in ecosystems involve its transformation and movement through various organic, inorganic and microbial pools. Phosphorus is unique among essential nutrients due to the absence of a significant gaseous phase in its natural cycle, which makes its movement and recycling highly localized (Vitousek et al*.,* 2010). These processes include mineralization, immobilization, adsorption, desorption, leaching, biological uptake (Turner et al*.,* 2002) runoff, sedimentation and resuspension.

In terrestrial ecosystems, phosphorus mainly originates from the breakdown of phosphatic rock minerals and is present in both organic and inorganic fractions. Yet, a large portion of soil phosphorus becomes tightly bound to iron, aluminium or calcium compounds, which makes it less available to plants. As a result, phosphorus frequently considered as the second most limiting nutrient after nitrogen terrestrial environments (Turner et al., 2002). Whereas, in aquatic environments, phosphorus presents mainly as dissolved inorganic phosphorus (DIP), dissolved organic phosphorus (DOP) and particulate phosphorus (PP). phosphorus in these systems is highly mobile and rapidly cycled by phytoplankton and microbial communities, as much faster than in soils of terrestrial ecosystems (Jin et al., 2024).

Human activities over the past century have intensified the global phosphorus cycle. In agriculture, phosphorus deficiency is typically managed using inorganic phosphate fertilizers. However, overuse of these fertilizers is not only economically unsustainable but also environmentally detrimental. However, these fertilizers are utilized with very low efficiency, leading to accumulation of phosphorus in soil. High phosphorus application from agriculture, especially through runoff and soil erosion, is a key driver of eutrophication in waterbodies. This nutrient enrichment promotes excessive algal growth, low oxygen environment and ultimately deteriorate water quality and aquatic biodiversity (Cordell et al., 2009, Alewell et al., 2020; Duhamel, 2025).

2. PHOSPHORUS IN DYNAMICS IN TERRESTRIAL ECOSYSTEMS

Forms of Phosphorus: Soil P exists in various chemical forms including inorganic P (Pi) and organic P (Po). These P forms differ in their behaviour, fate in soils and availability to plants (Brady and Weil, 2008).

Organic P (Po): The amount of organically bound phosphorus (Po) in soils can differ widely depending on the soil type. Globally, soil Po is estimated to range between 7 and 1056 mg P kg^{-1} of soil, making up roughly 20–80% of the total phosphorus pool (Campbell and Racz, 1975). Much of this Po comes from the breakdown of plant and animal residues, supported by soil microorganisms and fauna (Stutter et al., 2012). In addition, phosphorus applied through fertilizers can be immobilized into organic forms. Microorganisms play a key role in this process, converting inorganic phosphorus (Pi) into Po for incorporation into their biomass (Brady & Weil, 2008; Syers et al., 2008).

Soil Po can be grouped into two categories such as stabilized forms like inositol phosphates and phosphonates and more active forms like orthophosphate monoesters and organic polyphosphates (Condron et al., 2005; Nash et al., 2014).

Inorganic phosphorus (Pi): Inorganic phosphorus (Pi) is mainly present in soils as the ions $H_2PO_4^-$ and HPO_4^{2-}, which are adsorbed onto iron and aluminium oxides or hydroxides, clay, organic matter or bound to calcium compounds (Olibone and Rosolem, 2010).

2.1 Calcium or Magnesium Phosphate

These compounds are not found in soils at low soil pH but are stable, insoluble and dominant in neutral or alkaline soils [Brady and Weil, 2008, Shen, et al., 2011] They occur in soils in several forms and the most important forms are:

1. $Ca(H_2PO_4)_2.H_2O$, monocalcium phosphate, which is the water-soluble component of superphosphate that is transformed to less soluble products.
2. $CaHPO_4.2H_2O$ and $CaHPO_4$, dicalcium phosphate, both hydrated and the unhydrated forms that are slightly soluble in water.
3. $Ca_8H_2(PO_4)_6.5H_2O$, octacalcium phosphate.
4. $Ca_3(PO_4)_2$, tricalcium phosphate.
5. $Ca_{10}(PO_4)_6.(OH)_2$ (hydroxyapatite).
6. $Ca_{10}(PO_4)_6F$ (fluorapatite) and
7. $MgNH_4PO_4.6H_20$ (struvite) which is alkaline and water-soluble (Tisdale et al., 1985; Shen, et al., 2011; Kruse et al., 2015)

Iron and aluminium phosphates: A number of aluminium and iron phosphate minerals occur in soils [Shen et al., 2011], these compounds are not found in soils at low soil pH. The most common aluminium phosphates in soils are

1. wavellite ($Al_3(PO_4)(OH)_3.5H_2O$) and
2. variscite ($AlPO_4.2H_2O$) [Brady and Weil, 2008]

Soil solution P: Soil solution phosphorus (P) refers to the phosphate ions dissolved in the soil solution, which remain in dynamic equilibrium with the more readily available (labile) P pool. The concentration of P in soil solution is generally very low, typically between 0.001 and 1 mg P L^{-1}, with an average of around 0.05 mg P L^{-1}. Plants absorb phosphorus mainly as $H_2PO_4^-$, HPO_4^{2-} or PO_4^{3-} ions, with the dominant form depending on soil pH (Shinjiro, 2003).

Pools of P: Soil phosphorus is generally grouped into three main pools, which differ in their availability to plants.

Non-labile or fixed phosphorus pool: This is the largest reservoir of soil P but is not readily available for plant uptake. It consists of primary minerals such as apatite, other insoluble inorganic phosphates and stable organic forms that mineralize only very slowly. Much of this phosphorus is tightly bound to soil minerals or trapped within aggregates, making it biologically and chemically inaccessible under normal soil conditions (Shen et al*.,* 2011).

2.2 Labile or Active Phosphorus Pool

This pool contains phosphorus forms that are more accessible to plants. It includes loosely adsorbed inorganic P, secondary phosphate minerals (such as calcium, iron or aluminium phosphates) and organic compounds that can be mineralized relatively quickly by microbial activity or enzymes. The labile pool is dynamic and sensitive to factors like plant demand, soil pH, moisture and biological processes (Shen et al*.,* 2011).

2.2.1 Soil solution pool

The smallest but most immediately important pool, as it provides the phosphorus directly available for root uptake. It is made up mainly of inorganic orthophosphate ions ($H_2PO_4^-$ and HPO_4^{2-}) with a small contribution from dissolved organic P (Shen et al*.,* 2011).

These three pools are interlinked and exist in a state of dynamic equilibrium. As plants deplete phosphorus from the soil solution, the labile pool replenishes it. In turn, when the labile pool becomes exhausted, the fixed phosphorus pool slowly releases small amounts of P. However, this transfer is very gradual because of the strong chemical binding and stability of the fixed forms (Alewell et al*.,* 2020; Prasad and Chakraborty, 2019).

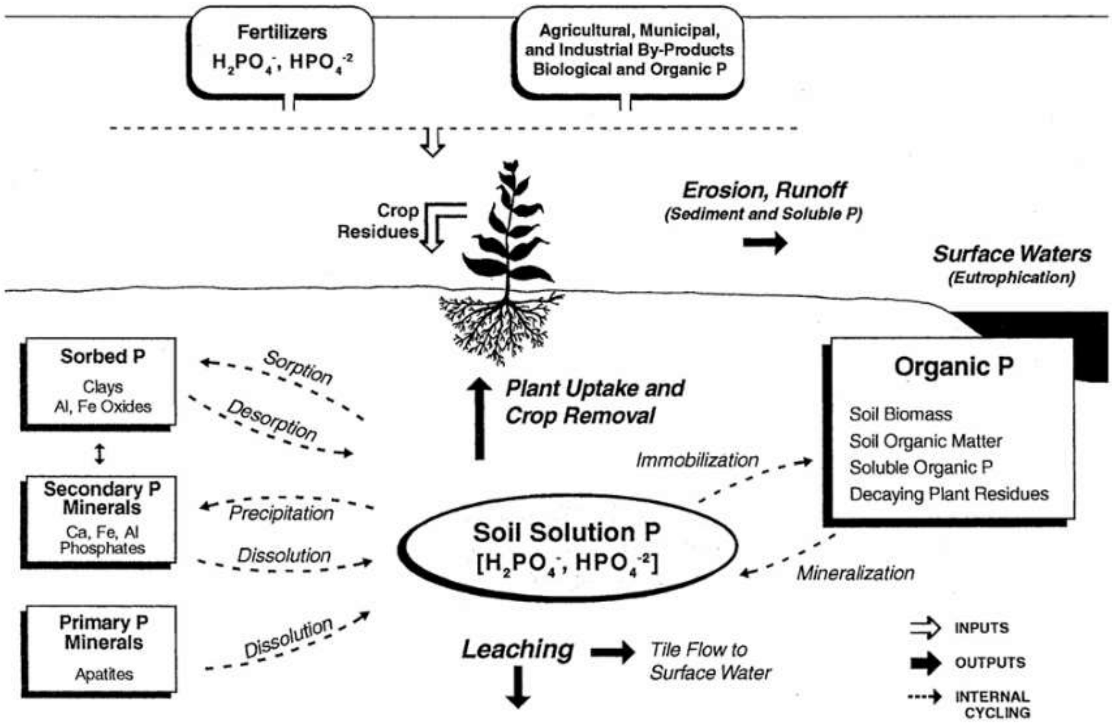

Fig. 1. Phosphorus cycle in terrestrial ecosystem (Pierzynski et al., 2002)

Phosphorus cycling in terrestrial ecosystem: Phosphorus (P) cycling in soils is highly complex, governed by interactions among inorganic and organic phases, biological activity, soil solution chemistry and environmental factors. The key chemical and biological processes driving P dynamics include dissolution–precipitation, sorption–desorption and mineralization–immobilization processes (Havlin et al*.,* 2014).

Phosphorus enters into an environment such as addition of chemical fertilizers, manures and crop residues in agricultural systems which help overcome the naturally low availability of soil phosphorus (Withers and Johnston, 2018). Whereas, grassland ecosystems depend largely on internal nutrient cycling, with phosphorus being returned to the soil through litter decomposition and root turnover, also grazing animals further influence its addition by dung and urine. In forests system, phosphorus mainly comes from organic matter decomposition, minor atmospheric inputs and slow mineral weathering, with litterfall and microbes recycling it efficiently despite low soil availability (Richardson et al*.,* 2009).

On the biological side, mineralization and immobilization are the main processes converting P between organic and inorganic forms. Mineralization is carried out by microbes and plant roots, releasing orthophosphate ($H_2PO_4^-$, HPO_4^{2-}) from organic matter through phosphatase enzymes. In contrast, immobilization occurs when microbes take up inorganic P into their biomass while decomposing residues with high C:P ratios (>300:1), temporarily reducing plant availability. Upon microbial turnover, this P is eventually re-mineralized (Stewart and Tiessen, 1987).

Sorption–desorption processes regulate the equilibrium between solid-phase and solution P. Orthophosphate ions attach to hydrous oxides, clays and carbonates by monodentate (more labile) or bidentate (less labile) bonds. Sorption is often a precursor to precipitation, which occurs when solution P exceeds solubility limits, leading to the formation of secondary Ca-, Al- or Fe-phosphates. Released of precipitated phosphorus called as dissolution, have low rate of release (Pierzynski et al*.,* 2002). adsorption and precipitation reactions are reversible, so P remains plant-available and also susceptible to runoff, erosion and leaching losses. In summary, soil P cycling is governed by tightly linked chemical and biological processes, which explain both its limited availability to plants and its vulnerability to environmental loss.

2.2.2 Challenges

Phosphorus fixation: Several chemical processes control how phosphorus (P) is stored or released in soils, shaping its transformation among different forms. A key factor is soil pH, which governs P availability by influencing its binding to iron and aluminium oxides, clay particles, and calcium carbonate ($CaCO_3$) (Johan et al*.,* 2021).

Table 1. Phosphorus dynamics in different terrestrial ecosystem

Ecosystem Type	Key Features of P Dynamics	Influencing Factors	References
Tropical Forests	High P weathering but most P quickly immobilized in organic matter or bound to Fe/Al oxides; low plant available P	Warm, wet climate; high organic matter turnover	Vitousek et al*.,* (2010)
Temperate Forests	Moderate P cycling; litterfall adds organic P; soils retain P better than tropics	Warm, wet climate; high organic matter turnover	Johnson et al*.,* (2003)
Boreal Forests	Slow P cycling; low availability; accumulation in organic layers due to slow decomposition	Seasonal climate; moderate decomposition	Chapin et al*.,* (2011)
Grasslands	P mostly in soil organic matter and roots; turnover depends on grazing/fire	Cold, acidic soils; slow microbial activity	McGroddy et al*.,* (2004)
Agricultural Soils	P availability influenced by fertilizers and cropping; risk of depletion or accumulation	Fertilizer management; crop rotation; soil texture	Sharpley et al*.,* (1994)

In neutral-to-calcareous soils: Phosphorus (P) retention in soils is largely governed by precipitation reactions (Lindsay et al., 1989), particularly with calcium, leading to the formation of increasingly insoluble compounds. In addition, P can be adsorbed onto the surfaces of calcium carbonate ($CaCO_3$) (Larsen, 1967) and clay minerals (Devau et al., 2010).

$$CaH_4(PO_4)_2 + CaCO_3 \longrightarrow Ca_2H_2(PO_4)_2 + CO_2 + H_2O$$

Monocalcium P   Calcium carbonate   Dicalcium phosphate
Less soluble

$$Ca_2H_2(PO_4)_2 + 3\ CaCO_3 \longrightarrow Ca_3(PO_4) + 3\ CO_2 + 3H_2O$$

Tricalcium phosphate
Very Less soluble

$$Ca_3(PO_4) + 3\ CaCO_3 \longrightarrow Ca_{10}(PO_4)_6.(OH)_2 + 3\ CO_2 + 3H_2O$$

Hydroxy apatite
Extremely insoluble

In acidic soils: Most of the reactions occurs when H_2PO_4 react with surface of oxides of iron, aluminium and manganese, involve in various reactions as given under

2.3 Precipitation and Adsorption Reactions

When orthophosphate concentrations are low, phosphorus is mainly retained through adsorption onto the surfaces of crystalline clay minerals, sesquioxide's or carbonates (Gerard, 2016). In contrast, at higher orthophosphate concentrations, soluble P tends to precipitate with metal cations, forming Fe and Al phosphates in acidic soils (Gerard, 2016).

These processes are strongly pH dependent. In acidic soils, Al and Fe ions readily react with dissolved $H_2PO_4^-$ to form insoluble hydroxyl phosphates, which effectively lock up phosphorus and make it largely unavailable for plant uptake.

2.4 Anion Exchange Reaction in the Phosphorus Fixation Process

Anion exchange reactions occur when negatively charged orthophosphate ions are attracted to positively charged sites that develop under acidic conditions, particularly on the surfaces of aluminium or iron oxides and the broken edges of kaolinite clays (Havlin et al., 2013).

2.5 Phosphorus Adsorption via Ligand Exchange on Aluminium Oxides

In this process, phosphate attaches directly to exposed surface sites, forming covalent bonds without a water molecule acting as a bridge. At first, phosphorus links to a single aluminium ion through an Al–O–P bond, where it remains

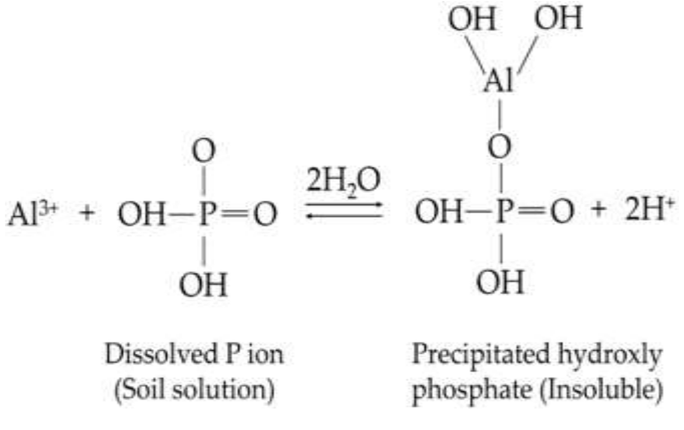

Fig. 2. Precipitation reaction in the phosphorus fixation process [Brady and Weil, 2008,]

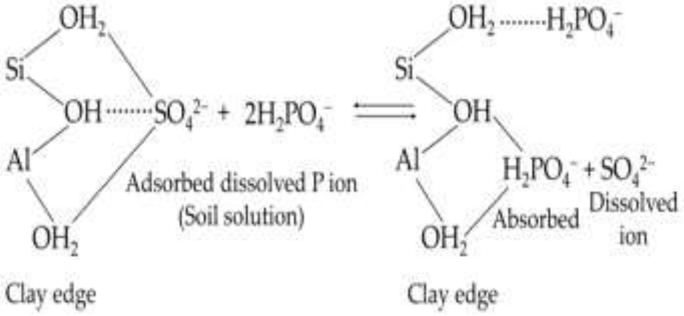

Fig. 3. Anion exchange reaction in the phosphorus fixation process [Brady and Weil, 2008]

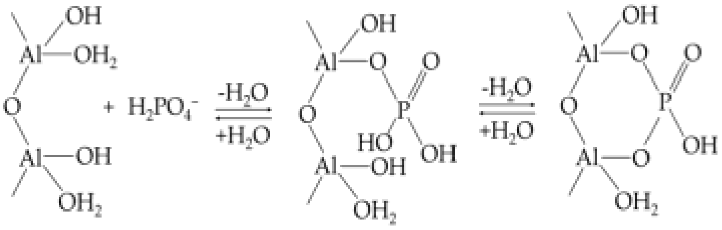

Fig. 4. Phosphorus adsorption via ligand exchange on aluminium oxides [Brady and Weil, 2008]

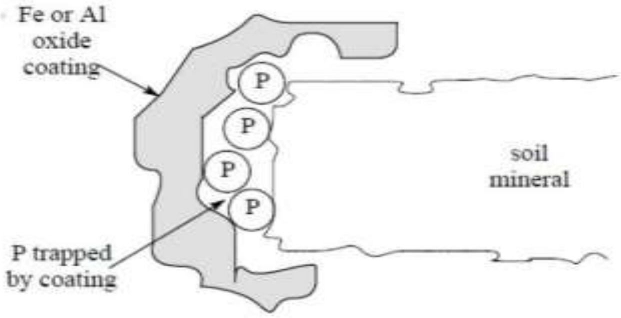

Fig. 5. The occlusion of adsorbed phosphorus Syers & Cornforth, 1983)

relatively easy to release. As the reaction progresses, a second oxygen atom from the phosphate replaces another hydroxyl group, producing a stable ring structure that connects two aluminium ions. Once this bond network is established, the phosphorus becomes tightly incorporated into the oxide mineral, making its return to the soil solution highly unlikely.

2.6 The Occlusion of Adsorbed Phosphorus

adsorbed phosphorus can become trapped when iron or aluminium oxide coatings precipitate onto soil mineral surfaces. Once enclosed in this way, the phosphorus is referred to as occluded P (Syers & Cornforth, 1983).

Phosphorus use efficiency and accumulation of phosphorus: The widespread use of phosphorus (P) fertilizers has been central to boosting crop yields, but their efficiency is relatively poor, with crops typically absorbing only 18–20% of the applied P in the year of use (Sattari et al., 2012). The remainder is largely immobilized in the soil through sorption and precipitation, leading to the gradual build-up of legacy P. This creates a twofold problem like, while soils may contain substantial total P reserves, much of it remains inaccessible to plants and excess P can be lost through runoff and erosion, contributing to eutrophication in aquatic systems. Addressing this issue requires improving phosphorus-use efficiency by enhancing crop uptake and developing approaches to better mobilize and utilize legacy P reserves.

Factor influencing Phosphorus dynamics: As discussed in the previous section, P gets transformed and fixed into less available P forms in the soil. A number of factors that involved in these transformations which are discussed in this section:

pH: Soil pH plays a critical role in regulating phosphorus (P) availability to plants. In general, the relative availability of P species follows the trend $H_2PO_4^- > HPO_4^{2-} > PO_4^{3-}$, though this order varies with soil pH (Havlin et al., 2013). At near-neutral pH (~7.2), the monovalent ($H_2PO_4^-$) and divalent (HPO_4^{2-}) orthophosphate species occur in approximately equal proportions. P availability is highest at near-neutral soil pH, where both adsorption and precipitation processes are minimized (Mishra et al., 2017; Blaise et al., 2018).

Cation/Anion effects: Soils with higher concentrations of di- and tri-valent cations (*e.g.* Ca^{2+}, Mg^{2+}, Al^{3+}, Fe^{3+}) generally exhibit greater P-fixation capacity compared to those dominated by monovalent cations. As a result, phosphorus availability to plants is reduced (Blaise et al., 2018).

Soil texture: Soils with finer texture are generally more prone to phosphorus fixation than coarse-textured soils, as the extent of fixation is strongly influenced by clay content. The mechanism of fixation in clay-rich soils occurs primarily through two pathways: (i) adsorption of phosphate ions onto the positively charged edges of clay minerals and (ii) specific adsorption by the oxides of Fe and Al associated with clay surfaces (Blaise et al., 2018).

Hydrous oxides of Fe/Al: Fe/Al oxides and hydrous oxides are abundant in acidic soils and their presence is primarily responsible for the high phosphorus (P) retention observed in these soils. The active forms of Al and Fe are commonly associated with both organic fractions (mainly Al–humus complexes) and mineral fractions (such as ferrihydrite). These oxidized secondary minerals strongly interact with phosphate ions, binding them either through adsorption or precipitation reactions. As a result, P becomes temporarily unavailable to plants and microbes (Havlin et al., 2014).

Calcium carbonate: In calcium-rich calcareous soils, the solubility of phosphorus (P) is largely governed by reactions with calcium compounds. Much of the P becomes fixed either through the formation of dicalcium phosphate or by attaching to calcite surfaces, where it forms stable calcium–carbonate–phosphate complexes (Havlin et al., 2014).

Silicate minerals: Soils formed from volcanic ash, such as Andisols, have an exceptionally high capacity to retain phosphorus (P) (Mishra et al., 2017). Among clay minerals, kaolinitic clays fix more P than smectite or montmorillonite clays. This is because kaolinite has variable charges, particularly along its crystal edges, which provide favourable sites for phosphate binding (Blaise et al., 2018).

Soil organic matter (SOM): Soil organic matter (SOM) is the main reservoir of organic phosphorus (P) in soils. This is because organic matter decomposition releases different organic anions that can bind with Fe and Al, forming stable complexes. These complexes prevent Fe and Al from reacting with phosphate ions, thereby reducing the formation of non-labile

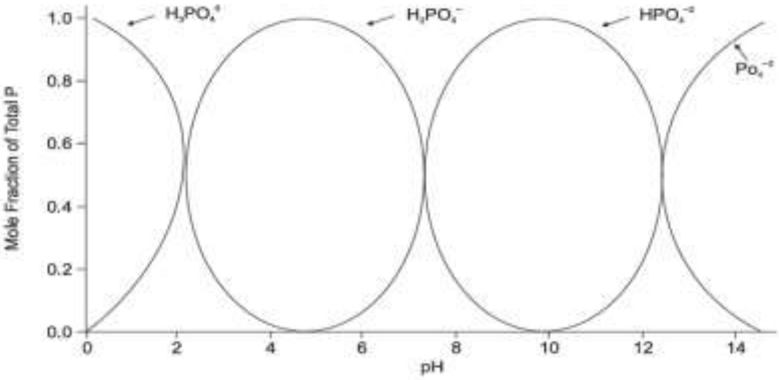

Fig. 6. Relation of pH with mole fraction of total P

Table 2. Microorganisms commonly involved in soil and plant interactions

Bacteria	*Bacillus sp., Bacillus circulans, B.cereus, B.fusiformis, B. pumils, B. megaterium, B. mycoides, B. polymyxa, B. coagulans B,.chitinolyticus, B. subtilis, Pseudomonas sp., P putida, P. striata, P. fluorescens,*
Fungi	*Aspergillus awamori, A. niger, A. tereus, A. flavus, A. nidulans, A. foetidus, A. wentii. Fusarium oxysporum,*
Actinomycetes	*Actinomyces, Streptomyces.*
Cyanobacteria	*Anabena sp., Calothrix braunii, Nostoc sp., Scytonema sp.,*
VAM	*Glomus fasciculatum*

(unavailable) P and helping maintain P in more available forms (Mishra et al*.,* 2017).

Microbial biomass: Soil microbial biomass plays a key role in phosphorus (P) dynamics. First, it acts as the main driver in converting organically bound P into plant-available forms such as solution and labile P. Second, it serves as a reservoir, temporarily storing a significant pool of P within microbial cells. Beyond these direct roles, microbes also influence P availability indirectly—by altering soil pH and releasing organic molecules during the decomposition of organic matter, which can further mobilize P (Mishra et al*.,* 2017).

Anaerobic condition: Under waterlogged or anaerobic conditions, phosphorus (P) is often released into the soil solution through the reductive dissolution of ferric hydroxides that hold P. This makes the redox status of a soil a critical factor in determining its ability to retain or release P. Other contributing mechanisms include the dissolution of occluded P, enhanced mineralization of organic P in acidic soils and increased solubility of calcium-bound P in calcareous soils. Together, these processes improve P mobility and diffusion, thereby influencing its availability to plants (Havlin et al*.,* 2017).

Soil Microorganisms Mediating Phosphorus Availability: Microorganisms are central players in soil phosphorus (P) dynamics, as they strongly influence the availability of P to plants (Richardson and Simpson, 2011). Soil microorganisms improve the ability of plants to access P through several complementary mechanisms:

Stimulation of root growth and development: Microbes can enhance root acquisition capacity either via symbiotic associations such as mycorrhiza, which extend the effective root system or by producing hormones that stimulate root growth, branching and root hair formation. For example, microbial production of indole-3-acetic acid (IAA), gibberellins (GAs) and enzymes such as 1-aminocyclopropane-1-carboxylate (ACC) deaminase alters plant ethylene metabolism, leading to improved root architecture (Richardson and Simpson, 2011; Hayat et al*.,* 2010).

Modification of soil P equilibria: Microorganisms can shift sorption–desorption dynamics, thereby increasing the net transfer of orthophosphate ions into soil solution. They may also enhance the mobility of organic P, either directly through the release of exudates or indirectly via microbial turnover (Seeling and Zasoski, 1993).

2.7 Direct Solubilization and Mineralization of P

This includes proton and organic acid efflux, production of siderophores that chelate Fe and Al, and secretion of extracellular enzymes such as phosphatases and cellulolytic enzymes, which hydrolyze organic P compounds and mineralize plant residues (Ryan et al*.,* 2001). Biodiversity of PSM (Sharma et al*.,* 2013).

Management: Improving phosphorus management in agricultural systems involves addressing low nutrient use efficiency, P fixation and the accumulation of legacy phosphorus in soils. Applying fertilizers in a balanced manner on based of soil testing, can prevent over-application and reduce unnecessary buildup (Withers et al*.,* 2014). Advanced fertilizers, such as slow-release types or those enriched with organic acids, help limit fixation and improve plant availability of phosphorus (Shen et al*.,* 2011). Incorporating organic amendments like compost or manure enhances soil microbial activity, which mobilizes bound phosphorus (Nziguheba et al*.,* 2016). The use of phosphate-solubilizing microorganisms and mycorrhizal fungi also increases plant access to fixed phosphorus (Richardson and Simpson, 2011). Additionally, agronomic practices like crop rotation, cover cropping and minimum tillage improve phosphorus mobilization and root uptake (Simpson et al., 2011). Emerging strategies focus on mobilizing legacy phosphorus through microbial inoculants, manipulating root exudates and breeding crops with higher phosphorus-use efficiency, offering sustainable long-term solutions (Rowe et al., 2016).

Phosphorus in Aquatic Ecosystems

Forms of P in aquatic system (Jarvie et al., 2002)

Table 3. Classification of phosphorus forms in the environment

Category	Sub type	Examples	Notes
Dissolved Inorganic P	Orthophosphate ions	$H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}	Most bioavailable form of P
	Condensed inorganic phosphates	Pyrophosphate, metaphosphate, polyphosphates	Hydrolyzable to orthophosphate
Dissolved Organic P	Condensed organic phosphates	ATP (adenosine triphosphate)	Biologically active energy molecules
	Other organic P compounds	Sugar phosphates, inositol phosphates, phospholipids, phosphoproteins, phosphoamides	May require enzymatic hydrolysis to be bioavailable
Particulate Organic P	Cellular material	Associated with plant, animal, and bacterial biomass	Includes both structural and storage forms
Particulate Inorganic P	Mineral P forms	Hydroxyapatite, brushite, fluoroapatite, variscite, stringite, wavellite	Often derived from geological or sediment sources
	Sorbed P	Bound to clays, clay-organic complexes, metal oxides/hydroxides	Typically less available; can be released under changing redox/pH conditions

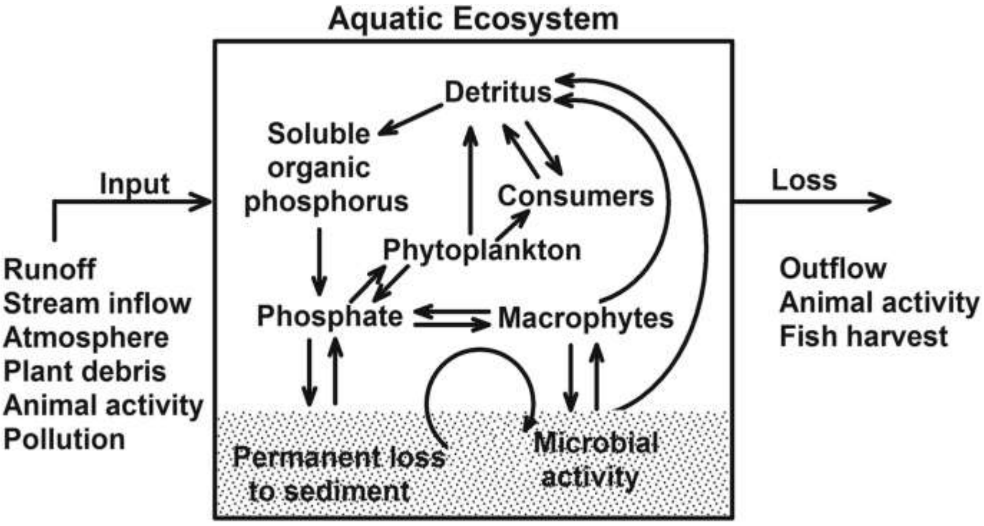

Fig. 7. Aquatic ecosystem

Phosphorus cycling in aquatic ecosystem: Phosphorus dynamics in aquatic ecosystems, including rivers, lakes, wetlands and oceans, are governed by a complex interplay between inputs, internal cycling and outputs. In aquatic ecosystems, phosphorus enters mainly through runoff, stream inflow, atmospheric deposition, plant debris, animal activity and pollution (Smith et al*.,* 2006). phosphorus occurs primarily as dissolved inorganic forms, such as phosphate and dissolved organic forms, which is readily taken up by phytoplankton and macrophytes, supporting primary production. Through consumption, phosphorus moves to higher trophic levels and upon death or excretion, organic matter and detritus return phosphorus back into the water. Microbial activity plays a key role in mineralizing organic phosphorus into soluble forms, making it available again for uptake.

Sedimentation represents a significant pathway for phosphorus loss from the active cycle, as particles settle to the benthic zone where phosphorus may become permanently buried or temporarily stored in sediments. Under certain conditions, such as hypoxia, sediment-bound phosphorus can be released back into the water column, a process known as internal loading, which can exacerbate eutrophication. Output pathways include water outflow, fish harvest, and animal migration, which remove phosphorus from the system. The balance between these inputs, transformations, and losses determines the trophic status of the water body and its susceptibility to nutrient enrichment problems.

Challenges: High phosphorus inputs from agricultural runoff, erosion, sewage discharge and industrial waste are among the main causes of eutrophication in aquatic ecosystems. Because phosphorus usually limits productivity in these systems, its excess availability fuels explosive growth of algae and phytoplankton, often resulting in harmful blooms. As these blooms collapse and decompose, oxygen levels in the water are depleted, creating hypoxic or anoxic conditions that harm fish and other aquatic organisms. In addition, phosphorus that has accumulated in sediments can be released back into the water under oxygen-poor conditions, further intensifying eutrophication through internal recycling. This feedback loop leads to long-term declines in water quality, disrupts ecosystem balance, and poses serious ecological and human health challenges.

A groundwater quality assessment in the Palar and Cheyyar River basins of Tamil Nadu revealed that over one-third of samples contained phosphate concentrations above permissible drinking water standards, with agricultural inputs identified as the main source of contamination and a call made for improving fertiliser efficiency (Rajmohan and Elango, 2005). By contrast, a study in the north-central and north-western agricultural regions of Sri Lanka showed that fertiliser use was often six to ten times higher than government recommendations; however, phosphate levels in groundwater generally remained within safe limits. Nonetheless, some lakes in the region exhibited high concentrations (>21.7 mg l^{-1}) and signs of eutrophication, attributed to excessive fertiliser application and livestock use of water bodies (Young et al*.,* 2010).

Management: Managing eutrophication mainly involves cutting down the flow of excess nutrients especially phosphorus and nitrogen that fuel algal blooms and oxygen loss in water bodies.

Table 4. Comparative analysis of P dynamics in different ecosystems

Aspect	Terrestrial ecosystem	Aquatic ecosystem	Wetland ecosystem	Agroecosystem
Dominant P form	Inorganic +organic P	Dissolved Reactive P	Organic and Dissolved Reactive P	Inorganic (Fertilizer-based)
Key inputs	Weathering, litter	Runoff, Sediment	Runoff, Sediment	Fertilizer, Manure
Outputs	Leaching, uptake	Sedimentation, Algal Uptake	Sedimentation	Crop Harvest, Runoff
P retention mechanism	Soil binding (Fe and Al oxides)	Sediment adsorption	Sediment adsorption	Soil fixation, Accumulation
Limiting Factor	Organic P mineralization	Internal loading	Internal loading	Over-application, Erosion
Human impact	Low to medium	High (eutrophication)	High (eutrophication)	Very high

Effective measures include upgrading wastewater treatment systems to better remove nutrients, using precision farming to limit fertilizer losses, creating buffer zones and wetlands to filter runoff and applying responsible manure management practices. Within lakes, short-term fixes such as aeration, adjusting fish populations or applying phosphorus-binding agents like alum can help, but lasting improvements depend on reducing nutrient pollution at the watershed scale (Paerl et al., 2016). In the long run, tackling eutrophication successfully requires a mix of practical technologies, strong policies and active involvement from local communities and stakeholders.

3. CONCLUSION

- Phosphorus availability and cycling differ across terrestrial and aquatic ecosystems due to fixation in soil and mobility in aquatic ecosystem.
- Human-induced inputs (*e.g.* fertilizers, runoff) disrupt natural P dynamics, causing issues like eutrophication which cause negative impact on human and biodiversity.
- Long-term P buildup in soil, which can contribute to environmental pollution even years after inputs stop thus there is need to utilized accumulated phosphorus in agroecosystem.
- Phosphorus fixation in soils and low use efficiency limit crop productivity and demand improved management approaches.
- Studying phosphorus dynamics is key to sustainable nutrient management, environmental protection and food security.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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