Transformation of Phosphorus under Anoxic Submerged Soil Environment

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ABSTRACT

Submerged soils, initially formed under upland conditions and later waterlogged due to rising groundwater, flooding, excessive irrigation or sea level rise, present unique challenges for nutrient availability, especially phosphorus (P). Under anoxic conditions, submergence alters soil redox potential and pH, significantly influencing P dynamics. In the early stages, phosphorus availability increases due to processes such as organic matter mineralization, solubilisation of Fe and Al-bound phosphates, and reductive dissolution of iron oxides. However, over time, phosphorus availability declines as fixation occurs through interactions with clay minerals like kaolinite, montmorillonite, and hydrous oxides of Fe and Al. Thus, emphasis on the importance of understanding the complex behaviour of phosphorus in submerged, anoxic environments for effective nutrient management is crucial.

INTRODUCTION

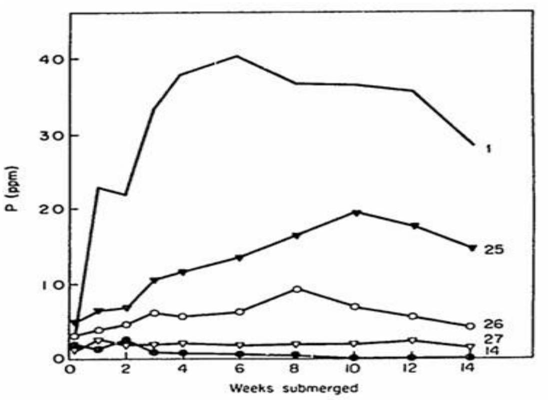
Soil plays a critical role in agriculture, serving as the prime source of nutrients essential for crop development. Although agricultural soils are typically exposed to air, a significant portion of the global population relies on crops cultivated in soils that remain submerged. The submerged soils, widely distributed worldwide, are originally formed under upland conditions but later became waterlogged due to factors such as rising groundwater levels, flooding, irrigation for rice cultivation or increases in sea level. The definition of submerged soils limits it to those soils containing dryland crops with temporary waterlogging. At the time of submergence, atmospheric gases like oxygen enters the soil interstitial water at much slower rate than that in gas filled pores through molecular diffusion (Ponnamperuma, 1972). However, the scarcity of oxygen is not uniform showing high concentration in the surface layer and practically zero at sub surface layers.

Phosphorus (P), the second major nutrient for plant growth is highly dependent on the soil pH conditions for its availability towards plants. As a result of submergence, the soil pH converses towards neutral value, i.e., increases in acid soil and decreases in sodic and calcareous soil (Ponnamperuma, 1972). Excess moisture containing anoxic soils with reducing conditions thus affect the P availability and solubility through altering the soil reaction conditions and chemistry of certain metal cations such as Fe which impact the fixation of P (Jayarathne et al., 2016; Nyamaizi et al., 2022).

Phosphorous transformation in submerged soils

Soil phosphorus is typically classified into three prominent forms: soluble, labile, and stable forms. The plants absorbs orthophosphates, specifically $H_2PO_4^-$ and HPO_4^{2-}. In soils, sediments, and natural waters, phosphorus exists in both organic and inorganic forms, ranging from truly soluble to slightly soluble compounds. These comprises of iron ($FePO_4$) and aluminium ($AlPO_4$) phosphates, phosphates adsorbed onto hydrous oxides of Fe^{3+} and Mn^{4+}, phosphates retained through anion exchange on clays and hydrous oxides, calcium phosphates, and organic phosphorus compounds. In acidic soils and sediments, phosphorus is predominantly associated with Fe^{3+} and Al^{3+}, whereas in neutral to alkaline soils, calcium phosphate forms are more prevalent.

Soil submergence is well established to affect the accessibility and transformation of native as well as applied phosphorus through the movement of orthophosphate ion. During the initial stage of submergence, the concentration of water soluble and available P increases, followed by periodic decline depending on the soil properties (Fig.1). These transformations are mediated by alterations in the Eh and pH (highest P solubility at low pH in submerged condition) of the flooded soil (Ponnamperuma, 1972).



Soil No.	Texture	pH	OM%	Fe%
1	Sandy loam	7.6	2.8	0.18
14	Clay	4.6	2.8	2.18
25	Sandy loam	4.8	4.4	0.18
26	Clay loam	7.6	1.5	0.30
27	Clay	6.6	2.0	1.00

Fig.1. Changes in water soluble-P in submerged soils of different properties (Ponnamperuma, 1972)

The initial increase in phosphate availability can be explained by following mechanisms (Ghildyal, 1976)-

a. Mineralization of organic residue releasing P

$$\text{Organic P forms} \underset{\text{Microbes}}{\overset{\text{Mineralizatio}}{\longleftrightarrow}} H_2PO_4^- \text{ (soluble phosphate)}$$

b. $FePO_4.2H_2O \xrightarrow{\text{Reduction}} Fe_3\ (PO_4).8H_2O \rightarrow FePO_4.2H_2O$ and $AlPO_4.2H_2O$ solubilisation by increased pH, reduction of acid soils.

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c. Reduction of hydrated ferric oxide coating followed by release of co-precipitated and occluded phosphorus

d. Organic anions mediated displacement of P from aluminium and ferric phosphates

e. Due to CO_2 emission in calcareous soil, pH decreases, thus solubility of calcium phosphates increases

f. Anion exchange between clay or organic anions and phosphate release of P.

The reduction in available phosphorus (P) concentration during prolonged submergence might be attributed to its fixation by clay colloids such as kaolinite, montmorillonite, and hydrous oxides of aluminium and iron. These fixation processes in submerged soils can be represented by reactions such as:

$$\underset{\text{(Soluble)}}{Al^{3+} + H_2PO_4^-} + 2H_2O \rightleftharpoons 2H^+ + \underset{\text{(Insoluble)}}{Al(OH)_2H_2PO_4}$$

Furthermore, the incorporation of green manures also influences phosphorus dynamics in flooded soils by facilitating the transformation of inorganic P into organic forms. Additionally, phosphorus mobility may occur via downward movement with percolating water. Thus, submergence of the soil with water significantly alters the P dynamics in such soil affecting its availability in such conditions.

CONCLUSION:

Submergence profoundly influences soil phosphorus dynamics by altering its chemical environment, particularly redox potential and pH. Initially, the availability of phosphorus increases due to processes like organic matter mineralization, solubilisation of Fe and Al-bound phosphates, and reduction of iron oxides. However, with prolonged submergence, phosphorus tends to become fixed again through interactions with clay colloids and hydrous oxides, reducing its bioavailability. These transformations highlight the complex behaviour of phosphorus in flooded soils and underscore the importance of understanding site-specific soil properties for effective nutrient management under submerged conditions.

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