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PHOSPHORUS IN SOIL: FORMS, DYNAMICS, AND THE EFFECTS OF POULTRY MANURE AS ORGANIC FERTILIZATION

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Abstract *Phosphorus (P) is an essential macronutrient that plays a central role in plant metabolism, particularly in energy transfer, nucleic acid synthesis, membrane formation, and overall crop development. Although many soils contain substantial total phosphorus reserves, only a very small proportion is directly available to plants because most soil phosphorus occurs in poorly soluble inorganic compounds or in organic forms requiring biological mineralization. This paper presents a literature-based synthesis of the main forms of phosphorus in soil, the factors controlling its mobility and availability, and the effects of organic fertilization on phosphorus dynamics, with particular emphasis on poultry manure. The reviewed literature indicates that soil phosphorus behavior is governed by parent material, pH, mineralogical composition, soil texture, organic matter content, microbial activity, and long-term fertilization history. Organic amendments such as farmyard manure, compost, sewage sludge, and crop residues may increase phosphorus availability by contributing both organic and inorganic P, stimulating phosphatase activity, modifying sorption processes, enhancing microbial turnover, and improving soil aggregation. However, repeated or excessive organic fertilization may also result in phosphorus accumulation and elevated environmental risk through runoff, erosion, or leaching, particularly in coarse-textured soils or under phosphorus-surplus management. Poultry manure is of particular agronomic interest because of its relatively high phosphorus content and the presence of soluble and moderately labile P forms, which can enhance plant uptake but also increase the potential for off-site phosphorus transfer. Overall, sustainable phosphorus management requires the integration of agronomic and environmental considerations and a more comprehensive understanding of both organic and inorganic soil phosphorus pools.*

Keywords*: phosphorous in soil, poultry manure, organic fertilization.*

INTRODUCTION

Phosphorus is one of the major nutrients required for plant growth and agricultural productivity. It is indispensable for ATP-mediated energy transfer, cell division, nucleic acid synthesis, membrane structure, and root development. Despite its essentiality, phosphorus is frequently the nutrient most limiting crop production because its bioavailability in soil is often low, even where total P reserves are considerable (MAO et al., 2015). This apparent contradiction results from the fact that only a small fraction of total soil phosphorus is present in forms readily accessible to plants.

The phosphorus content of soil is initially inherited from the parent material from which the soil developed. Sedimentary rocks contain approximately 0.05-0.3% P2O5, crystalline rocks 0.2-0.7% P2O5, and magmatic rocks 0.3-1.0% P2O5 (SALA, 2007). According to total phosphorus reserves, soils may be classified as very low, low, moderate, or

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high in phosphorus content (LĂCĂTUȘU, 2006). For medium-textured soils, fertility status may also be evaluated on the basis of total phosphorus concentration and total reserve in the 0-20 cm horizon (LĂCĂTUȘU et al., 2017). Nevertheless, only about 0.5-1% of total phosphorus is usually available to plants at a given moment, due to the low solubility and limited mobility of most phosphorus compounds in soil (ANDRIEȘ, 2007).

Soil phosphorus occurs in both inorganic and organic forms. Inorganic phosphorus includes phosphate ions in solution, phosphate adsorbed on clay minerals and Fe/Al oxides, and phosphate precipitated as calcium, iron, aluminum, or magnesium salts. Organic phosphorus is associated with plant residues, microbial biomass, humus, nucleic acids, phospholipids, phytin, and related compounds (DAVIDESCU and DAVIDESCU, 1981; MÜLLER, 1965). The distribution and transformation of these forms are influenced by numerous physicochemical and biological factors, including soil pH, Fe, Al, Ca, and Mg concentrations, organic matter content, texture, structure, moisture, temperature, and microbial activity (ROWELL, 1994).

In many soils, organic phosphorus represents a substantial share of total P and may constitute an important reserve of potentially available phosphorus. However, this pool is often neglected in routine soil testing, which generally focuses on readily extractable inorganic phosphorus (FRANSSON and JONES, 2007; WYNGAARD et al., 2016, MARIN et al, 2022). This limitation is important in agricultural systems receiving organic amendments, because manure, compost, sludge, and crop residues may substantially alter the size, composition, and turnover of both organic and inorganic phosphorus pools. Among organic amendments, poultry manure deserves particular attention. It is widely used as a fertilizer because it provides both nitrogen and phosphorus, but its relatively low N:P ratio means that phosphorus may accumulate in soil when manure applications are based primarily on crop nitrogen requirements (SHEPHERD and WITHERS, 1999). Consequently, poultry manure may simultaneously improve crop nutrition and increase the risk of phosphorus losses to the environment.

The aim of this paper is to provide a structured synthesis of the literature concerning: (i) the forms and behavior of phosphorus in soil; (ii) the effects of organic fertilization on soil phosphorus dynamics; and (iii) the specific influence of poultry manure on phosphorus availability, plant uptake, and environmental risk.

MATERIAL AND METHODS

This study was developed as a narrative literature review based on the scientific sources provided in the initial report. The selected references include textbooks, monographs, and peer-reviewed journal articles addressing phosphorus chemistry in soils, phosphorus fractionation, phosphorus availability, organic matter interactions, long-term fertilization effects, and poultry manure management.

The literature was examined and organized into three main thematic areas:

(i) phosphorus occurrence and transformation in soil;
(ii) the effects of organic fertilization on phosphorus dynamics; and
(iii) the effects of poultry manure on phosphorus availability and redistribution in soil.

RESULTS AND DISCUSSIONS

3.1. Occurrence and forms of phosphorus in soil

The total phosphorus content of soil depends first on the nature of the parent material, but its subsequent distribution is controlled by pedogenesis, organic matter turnover, biological

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cycling, and agricultural management (SALA, 2007; LĂCĂTUȘU, 2006). From an agronomic perspective, total phosphorus alone is insufficient to describe fertility status, because only a very small fraction is present in a form readily accessible to plant roots. Organic phosphorus commonly represents 30-50% of total soil phosphorus, although broader intervals of 20-80% have been reported for many soil types (FRANSSON and JONES, 2007). It is concentrated predominantly in the upper horizons, where plant residues, microbial biomass, and humified organic matter accumulate. The main classes of organic phosphorus compounds include nucleic acids, phytin, lecithin, phospholipids, and related biomolecules (MÜLLER, 1965). These compounds enter the soil through plant residues, animal remains, microbial biomass, and their metabolic products. Their contribution to plant nutrition depends on the rate at which they are mineralized into orthophosphate forms.

The mineralization of organic phosphorus is closely linked to soil organic matter dynamics. ROWELL (1994) noted that in soils where organic matter content remains relatively constant, annual phosphorus release through mineralization may be limited. However, the humus-bound phosphorus fraction can still make a meaningful contribution to soil solution replenishment. The average C:N:P ratio of soil organic matter is approximately 100:10:1, and the balance between mineralization and immobilization depends strongly on organic matter composition and microbial demand (ANDRIEȘ, 2007). Inorganic phosphorus occurs in soil solution, in adsorbed forms, and in precipitated forms. In acid soils, phosphorus is predominantly associated with iron and aluminum compounds, whereas in neutral and alkaline soils it is more commonly associated with calcium salts. Adsorption and precipitation represent major mechanisms limiting phosphorus availability. Phosphate ions are readily adsorbed on clay minerals and Fe/Al oxides, while poorly soluble calcium, iron, and aluminum phosphates may precipitate depending on soil reaction and ionic composition. A dynamic equilibrium exists among phosphorus in solution, adsorbed phosphorus, and precipitated phosphorus. The phosphorus present in soil solution constitutes the immediately available pool for plants, but it is quantitatively very small, often amounting to only 0.3-0.5 kg ha^-1 in the 0-30 cm layer. Therefore, plant phosphorus nutrition depends not only on this instantaneous pool, but also on the ability of the solid phase to replenish it by desorption, dissolution, and diffusion.

BORLAN et al. (1994) described a series of processes controlling the phosphorus status of cultivated soils. Positive influences include phosphorus addition through mineral and organic fertilizers, seeds, dust deposition, upward transfer from deeper layers through roots, and faunal activity. Negative influences include phosphorus export with harvested crops, erosion losses, downward transfer through cracks, and leaching. The same authors also emphasized that phosphorus mobility is determined by the relationship between phosphorus concentration in solution and the amount of phosphorus in the solid phase capable of entering solution in real time. Thus, desorption, dissolution, diffusion, mineralization, and chelation tend to increase phosphorus mobility, whereas adsorption, precipitation, crystallization, occlusion, and microbial immobilization reduce it.

3.2. Role of organic phosphorus in soil fertility

Although routine soil testing commonly focuses on inorganic available phosphorus, organic phosphorus constitutes a major component of the soil phosphorus cycle and may contribute significantly to plant nutrition. FRANSSON and JONES (2007) emphasized that low-molecular-weight organic phosphorus compounds derived from roots and microorganisms can represent an important phosphorus source for soil microbial communities. Some of these

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compounds require prior dephosphorylation by phosphatase enzymes, while others may be taken up directly from the soil solution.

The agronomic significance of organic phosphorus is further supported by the work of WYNGAARD et al. (2016), who showed that phosphorus in the coarse soil fraction is related to soil organic phosphorus and to phosphorus mineralization estimated by isotopic dilution. Their findings suggest that improved estimation of organic P mineralization may strengthen fertilizer recommendations and contribute to more accurate assessments of plant-available phosphorus.

This issue is highly relevant because a large proportion of the world's soils are considered deficient in plant-available phosphorus, despite often substantial total phosphorus reserves (MAO et al., 2015). Consequently, relying exclusively on inorganic soil P tests may underestimate the nutrient-supplying capacity of soils rich in organic phosphorus.

3.3. Effects of organic fertilization on soil phosphorus dynamics

Organic fertilization plays an increasingly important role in nutrient management because it contributes nutrients, improves soil organic matter status, stimulates biological activity, and can modify the retention and release of phosphorus in soil. Organic amendments such as farmyard manure, compost, sewage sludge, crop residues, and green manures may affect phosphorus dynamics through direct P inputs, increased microbial turnover, altered sorption capacity, and changes in soil physical structure (ANNAHEIM et al., 2015; WANG et al., 2011).

Long-term field studies have shown that the effect of organic fertilization on soil phosphorus may vary depending on amendment type, application rate, and soil conditions. In some agricultural systems, repeated manure application led to an increase in organic phosphorus fractions, especially where soil organic carbon increased simultaneously. Such patterns were reported in long-term experiments in North America, Sweden, and the Netherlands, where manure inputs promoted the accumulation of both orthophosphate and organic P compounds, including orthophosphate monoesters (ANNAHEIM et al., 2015).

However, not all studies have confirmed a substantial long-term accumulation of soil organic phosphorus after organic amendment application. Annaheim et al. (2015) reported that, despite 62 years of contrasting fertilizer treatments, the composition of soil organic phosphorus remained relatively stable, whereas the main changes affected inorganic phosphorus pools. These results indicate that the long-term behavior of soil organic phosphorus may be governed more strongly by soil mineralogy, vegetation, and climate than by the annual addition of specific organic phosphorus forms.

The effect of organic fertilization on phosphorus availability may nevertheless be substantial. MAO et al. (2015) demonstrated that 17 years of combined organic and inorganic fertilization significantly altered soil phosphorus dynamics in a rice-wheat rotation system. Similarly, HUA et al. (2016), in a 29-year experiment, found that manure increased Olsen-P more strongly than straw incorporation when total phosphorus accumulation was similar. At the same time, they warned that prolonged excessive manure inputs can increase the risk of environmental phosphorus loss, whereas moderate manure rates and straw incorporation may provide a more balanced solution.

Organic amendments also influence the physical environment of phosphorus in soil. Soil aggregation is essential for maintaining structure, water infiltration, resistance to erosion, and nutrient retention. Macroaggregates generally contain more organic matter and higher nutrient concentrations than microaggregates. Humic substances, especially humic acids, contribute to aggregate cohesion and water stability (BLAGA and DUMITRU, 2001). WANG et al.

(2011) MARIN et al (2022) showed that long-term organic additions increased the proportion of large water-stable aggregates, improved the distribution of total C, N, and P across aggregate classes, and enhanced the effective supply of available phosphorus. Their results further suggested that moderate organic inputs may partly replace mineral fertilizers without compromising soil fertility.

Long-term fertilization also changes the relative proportions of labile and stable phosphorus pools. MOTAVALLI and MILES (2002), in the 111-year Sanborn Field experiment, found that manure and mineral fertilizers had significantly different effects on soil phosphorus fractions. Long-term manure application increased both labile and stable inorganic and organic phosphorus pools, indicating that phosphorus cycling in organically fertilized systems differs structurally from that in systems dependent mainly on mineral fertilizers.

Biological mechanisms are equally important. HU et al. (2009a) found that manure application increased plant biomass and the populations of bacteria involved in phosphorus mineralization and phosphorus solubilization. In a related study, Hu et al. (2009b) showed that arbuscular mycorrhizal fungi enhanced maize yield and phosphorus uptake in sandy loam soil under long-term phosphorus-deficient fertilization. These findings indicate that organic fertilization can increase phosphorus availability not only through chemical supply, but also by stimulating microbial and symbiotic processes involved in phosphorus acquisition.

The quality of the organic material is another decisive factor. NZIGUHEBA et al. (1998) observed that high-quality organic residues such as *Tithonia diversifolia* reduced phosphorus adsorption and increased unstable and moderately unstable soil phosphorus fractions. This effect was attributed to the competition of organic anions with phosphate for adsorption sites, as well as to the additional phosphorus contributed by the residue itself. By contrast, lower-quality residues such as maize stover produced much weaker effects. Therefore, the influence of organic amendments on phosphorus availability cannot be generalized without considering residue composition and decomposability.

3.4. Effects of poultry manure on soil phosphorus availability and redistribution

Poultry manure is one of the most phosphorus-rich organic fertilizers used in agriculture and contains an appreciable proportion of water-soluble, resin-extractable, and bicarbonate-extractable phosphorus forms (LEINWEBER, 1996). As a consequence, its agronomic effectiveness may be high, but so is its environmental significance. Waldrip et al. (2011) showed that poultry manure application stimulated the transformation of less mobile inorganic phosphorus and organic phosphorus into mobile inorganic forms within the rhizosphere. In perennial ryegrass, this resulted in increased phosphorus concentration in roots and enhanced total phosphorus uptake. The same study demonstrated that poultry manure increased the activities of acid phosphomonoesterase, alkaline phosphomonoesterase, and phosphodiesterase, particularly in rhizosphere soil, indicating intensified enzymatic mobilization of phosphorus (WALDRIP et al., 2011).

The high phosphorus loading potential of poultry production systems has long been recognized. SHEPHERD and WITHERS (1999) estimated that 1000 broiler chickens may excrete approximately 610 kg N, 225 kg P, and 315 kg K annually. They identified two main challenges associated with poultry manure management: the limited land area available for agronomically appropriate application, and the fact that the N:P ratio of poultry manure is lower than the nutrient ratio required by many crops. Consequently, manure application based on nitrogen demand often results in phosphorus oversupply and soil phosphorus accumulation. Soil type strongly influences the fate of poultry-manure-derived phosphorus. Shepherd and

WITHERS (1999) reported that, in sandy soils, poultry litter promoted phosphorus movement down the soil profile more readily than triple superphosphate. This deeper transport was attributed partly to the movement of organic phosphorus and partly to the lower phosphorus sorption capacity of coarse-textured soils. Such findings are especially important in regions where poultry manure is applied repeatedly over long periods.

Long-term field studies provide further evidence of phosphorus accumulation under poultry manure management. REDDY et al. (2009) showed that poultry litter applied at 100 kg N ha^{-1} helped maintain soil phosphorus near initial levels, whereas higher application rates promoted phosphorus buildup, particularly in no-tillage systems. They concluded that more sustainable cotton production could be achieved by combining moderate poultry manure application with winter rye as a cover crop and crop rotation.

At the microaggregate scale, poultry manure may significantly alter phosphorus distribution. RANATUNGA et al. (2013) reported that long-term poultry litter application increased Mehlich-3 extractable phosphorus, water-soluble phosphorus, bicarbonate-extractable labile phosphorus, and NaOH-extractable phosphorus across most microaggregate fractions. Such increases are agronomically relevant, but also environmentally significant because fine particles are more susceptible to transport by runoff, erosion, and wind.

Short-term column studies have also shown rapid movement and transformation of poultry-manure-derived phosphorus. GILES et al. (2015) found that maximum concentrations of total phosphorus, water-extractable phosphorus, orthophosphate, and myo-inositol hexakisphosphate in the soil profile coincided with high phosphorus saturation and peak dissolved phosphorus losses during the first weeks after application. These observations suggest that poultry manure may contribute both inorganic and organic phosphorus to downward transport, especially under saturated or leaching-prone conditions.

The form in which poultry-derived material is applied also influences phosphorus dynamics. AUDETTE et al. (2016a) showed that composted turkey manure supplied substantial quantities of moderately labile phosphorus. Although the labile phosphorus fraction was lower than in mineral-fertilized soils, ryegrass growth was greater in compost-amended soils after four weeks, suggesting that moderately labile phosphorus may be rapidly converted into plant-available forms through rhizosphere processes and microbial activity.

3.5. Agronomic benefits and environmental implications

The literature clearly indicates that organic fertilization, including poultry manure application, may improve soil phosphorus nutrition through several complementary mechanisms: direct nutrient input, enhanced microbial and enzymatic activity, reduced phosphorus sorption, improved soil structure, and increased aggregate stability (WANG et al., 2011; WALDRIP et al., 2011). In this sense, organic amendments are an important component of integrated nutrient management and may partially substitute mineral fertilizers under suitable conditions.

However, the same body of literature demonstrates that long-term or excessive applications can generate substantial phosphorus surpluses. These surpluses increase the accumulation of both labile and stable phosphorus fractions and raise the risk of phosphorus transfer to surface and subsurface waters through runoff, erosion, or leaching (Motavalli and MILES, 2002; HUA et al., 2016; RANATUNGA et al., 2013). This risk is especially pronounced in livestock-dense agricultural regions and in coarse-textured soils with low phosphorus sorption capacity (LEINWEBER, 1996; SHEPHERD and WITHERS, 1999).

McDowell et al. (2001) emphasized that phosphorus release to runoff is governed by an interaction among soil properties, climatic conditions, and fertilizer management. Therefore, the agronomic benefits of poultry manure and other organic amendments can only be sustained when phosphorus application is balanced against crop requirements and when soil phosphorus status is regularly monitored.

CONCLUSIONS

Phosphorus in soil occurs in a complex continuum of organic and inorganic forms whose availability is governed by parent material, soil reaction, mineralogy, organic matter, microbial processes, and management history. Although total soil phosphorus may be high, only a small fraction is immediately available to plants. Organic phosphorus represents an important component of total soil phosphorus and should be regarded as a significant reserve capable of contributing to plant nutrition through mineralization. Organic fertilization modifies soil phosphorus dynamics by supplying nutrients, stimulating microbial and enzymatic processes, influencing sorption reactions, and improving aggregate stability. Long-term organic fertilization may either increase soil organic phosphorus fractions or leave them relatively unchanged, depending on soil characteristics, amendment type, and environmental conditions. Its effect on inorganic and labile phosphorus pools is generally more pronounced and more consistently documented.

Poultry manure is a particularly effective phosphorus source because of its high phosphorus content and its substantial proportion of soluble and moderately labile forms. At the same time, repeated or excessive poultry manure application may lead to phosphorus accumulation and increased environmental risk, especially in coarse-textured soils and under phosphorus-surplus management. Sustainable phosphorus management should therefore integrate moderate application rates, crop-oriented nutrient planning, assessment of soil phosphorus fractions, and consideration of soil-specific vulnerability to phosphorus loss. Such an approach is necessary to balance agricultural productivity with environmental protection.

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