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The dynamics, analysis, and sustainable management of phosphorus in muck soils: a review

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Muck soils (Histosols) are vital and highly productive ecosystems for agriculture. However, managing phosphorus in these organic-rich systems presents a major challenge. Decades of fertilization have created large legacy phosphorus accumulation, while drainage and cultivation have altered soil pH increasing phosphorus immobilization by calcium interaction. Standard soil tests developed for mineral soils consistently fail to predict crop phosphorus needs in muck soils because their chemical extractants are often neutralized by high organic matter, and results confounded by dominant biological phosphorus cycling leading to inaccurate recommendations. This review provides new insights into how phosphorus behaves in muck soils and highlights the limitations of current soil tests in capturing this complexity. Bridging this gap is essential for both agronomic efficiency and environmental protection. The key recommendation is to move away from universal extractants toward the development of robust, regionally calibrated assessment tools. These tools must integrate key soil properties, such as organic matter, pH, and phosphorus-binding elements, to effectively guide sustainable nutrient stewardship in these vulnerable ecosystems.

KEYWORDS

eutrophication, Histosols, legacy phosphorus, phosphorus saturation ratio, soil testing

1 Introduction

Histosols, which account for about 1.3% of the global soil area, include roughly 7% of soils in the United States (US) (Kolka et al., 2016; Bai et al., 2025). These soils are typically found in areas with high water tables and are often formed in wetlands or glaciated regions (Zobeck et al., 2013). Muck soil plays a significant role in various ecosystems, particularly in agricultural regions. The inherent fertility, excellent water retention, and friable structure make them ideal for intensive agriculture (Bhadha et al., 2017). When drained for agricultural use, these organic soils become exceptionally fertile, making them a vital resource for cultivating high-value crops. In the US, regions such as the Everglades Agricultural Area (EAA) in Florida, the mucklands of Michigan, New York, Ohio, and California use these soils for cultivating vegetables like lettuce, celery, and onions, as well as specialty crops such as sugarcane (Harmer and Benne, 1941; Mukherjee and Lal, 2015; Sandoya and Lu, 2020; Bai et al., 2025).

Muck soil is distinguished by a high accumulation of organic matter, typically exceeding 20% (Frazier and Lee, 1971). As a result of more extensive microbial decomposition, muck soil is richer in mineral content and nutrients compared to peat soil (Reddy and DeLaune, 2008; Bai et al., 2025). Beyond their high organic matter and mineral content, muck soil

TABLE 1 Key differences in the composition, density, porosity, and phosphorus retention between organic muck soil (Histosols) and mineral soil in the surface horizon.

Characteristic	Muck soil (Histosols)	Mineral soil
Organic Matter %	Very High (>20%) (Reddy and DeLaune, 2008)	Very Low (<5%) (Reddy and DeLaune, 2008)
Dominant Composition	Decomposed plant material (organic matter) (Reddy and DeLaune, 2008)	Weathered rock-forming minerals (sand, silt, clay), primarily quartz and aluminosilicates (Reddy and DeLaune, 2008)
Bulk density	0.1–0.35 g cm^{-3} (Caron et al., 2015) and 0.41–0.44 g cm^{-3} (Castillo and Wright, 2008)	1–1.8 g cm^{-3} (Caron et al., 2015)
Total porosity	0.8–0.95 (Caron et al., 2015)	0.3–0.5 (Caron et al., 2015)
Primary P -binding agents	Ternary complexes of Ca^{2+}, organic matter, and P (Jindo et al., 2023) Calcium carbonate (Peng et al., 2021) Fe-Al and humic-fulvic acid fractions (Castillo and Wright, 2008).	In podzolic soils, Al is primary and then Fe (Kedir et al., 2022) In calcareous soil, while Ca and carbonate interactions dominate P retention, Fe and Al oxides also contribute when present (Pizzeghello et al., 2011) In calcareous soils (both organic and mineral), P binds to soil organic matter, specifically humic acids, through ternary complexes with calcium (Audette et al., 2020)
Phosphorus sorption capacity (PSC)	Negative correlation with organic matter (Organic acid competes with phosphate for sorption sites) (Daly et al., 2001)	Positive correlation with Al and Fe oxides (Daly et al., 2001)
P content: organic versus inorganic	In pasture muck soil, 78% of total P was in organic forms, versus 52% in cultivated muck soil (Castillo and Wright, 2008)	Low total P in organic form compared to muck soil. Inorganic form could be 20%–60% (Wang et al., 2022)
Microbial P content	Organic soil has microbial P up to 53% of TP. The amount is proportional to the organic matter content (Achat et al., 2010)	Mineral soil has microbial P in 1%–5% (Brookes et al., 1982) 2%–11% (Achat et al., 2010)
Role of pH in P retention	The higher pH of cultivated soil (6.8) favored P retention in Ca fractions. The lower pH of pasture soil (5.3) favored P retention in the humic-fulvic acid fraction. Tillage contributes to higher pH by incorporating bedrock limestone (Castillo and Wright, 2008)	A decrease in pH can promote the dissolution of Fe and Al oxides and hydroxides, leading to form Fe-P and Al-P complexes High pH can increase Ca^{2+} activity and carbonate concentration, leading to the precipitation of calcium phosphates (Penn and Camberato, 2019)
Water holding capacity	Extremely high (Williams et al., 2015)	Low (Williams et al., 2015)
CEC	Very high: 139–282 meq100 g^{-1} (MacLean et al., 1964)	Low: 1–50 meq 100 g^{-1} (Parfitt et al., 1995)

possesses several distinct characteristics. The influence of Aluminum (Al) and Iron (Fe) is particularly complex in the muck soil. For example, one study found a positive correlation of P with Fe, Manganese (Mn), and Al content (Becher et al., 2018), while other research suggests that muck soil is naturally low mineral content, making P immobilization by Fe and Al less prevalent under alkaline conditions (Zhi et al., 2024). Other studies have reported the formation of ternary complexes in muck soil involving minerals like [Fe, Al, Calcium (Ca)], humic substances, and P. For instance, Ca binds with organic matter, such as humic acid derived from muck soil, rather than directly binding with P minerals. It delays the formation of stable Ca-P or Al-P/Fe-P (Castillo and Wright, 2008; Jindo et al., 2023). Although muck soil is generally acidic, in regions like the EAA, drainage can cause mixing with underlying calcareous bedrock, which raises soil pH and introduces Ca-P precipitation as a new fixation mechanism (Wright et al., 2009). Muck soil also exhibits unique water retention capabilities and surface charge properties, which significantly influence its chemical reactivity and ecological function (Sokołowska et al., 2005). In addition to these chemical interactions, P binding is also influenced by the unique physical characteristics of muck soil, which differ from those of mineral soils (Table 1).

Cropped muck soils are rich in organic matter and total phosphorus (TP), necessitating careful monitoring to balance agronomic needs with environmental protection (Audette et al., 2018). However, the draining and cultivation of these soils trigger aerobic decomposition and soil subsidence, which fundamentally alter their structure and chemistry over time, creating complex management challenges (Bhadha et al., 2020). While these soils were historically acidic, decades of agricultural practices, including the incorporation of limestone bedrock have raised soil pH. This leads to high Ca levels, which can immobilize P, reducing its availability to plants (Wright et al., 2009). To compensate for this, additional P is commonly applied, even though the soil's TP content is already high (Hochmuth and Hanlon, 2016). While P fertilization is beneficial, its excessive or long-term application leads to soil P accumulation. Decades of agricultural production have often involved applying P fertilizers at rates exceeding crop removal to ensure maximum yields. This practice has led to a significant accumulation of legacy P in the soil profile, creating a large but often poorly available reservoir (McDowell and Haygarth, 2025). The loss of P creates significant environmental and economic challenges (Figure 1).

Environmentally, excess P from agriculture and wastewater leads to water pollution causing harmful algal blooms, hypoxia, and threats to aquatic biodiversity and human health, as well as closures of fisheries and recreational areas, which have direct economic consequences (Liu et al., 2008; Mallin and Cahoon, 2020). This practice is problematic, as excessive P, especially in dissolved forms can leach into nearby water bodies and cause

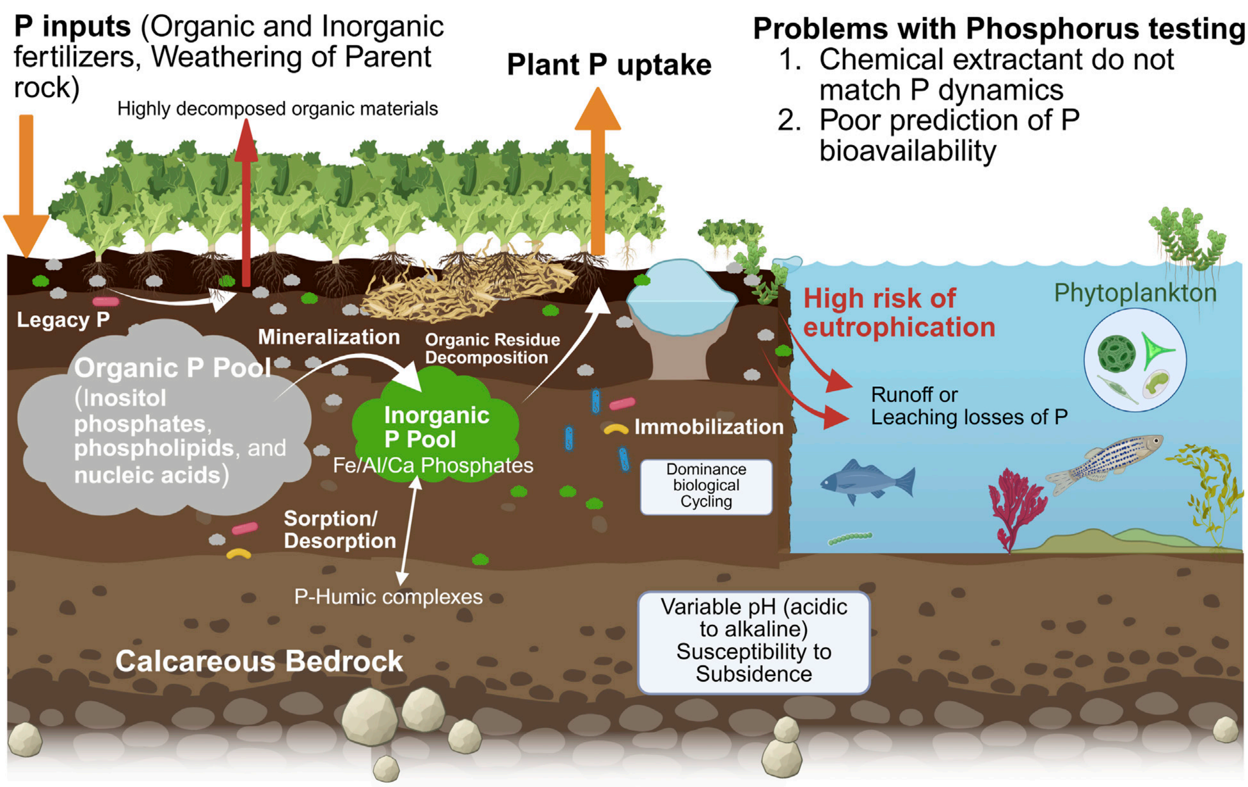

FIGURE 1
Conceptual diagram illustrating phosphorus (P) cycling and testing challenges in organic soils. P inputs from fertilizers, organic matter, and weathering contribute to both organic and inorganic P pools. Organic P undergoes mineralization to inorganic forms (Fe/Al/Ca phosphates), which interact through sorption/desorption and form P-humic complexes. Plant uptake and microbial immobilization regulate P availability, while variable pH and subsidence affect P dynamics. Inefficient P testing methods poorly predict bioavailable P, increasing the risk of runoff and eutrophication in nearby water bodies. This figure was created using BioRender (https://biorender.com/).

eutrophication (Steinman and Ogdahl, 2016). Reducing nitrogen (N) inputs without reducing P can make eutrophication worse by favoring the growth of nitrogen-fixing cyanobacteria (Carpenter, 2008). Phosphorus accumulation can alter soil microbial communities, reduce microbial diversity, suppress beneficial P-mineralizing bacteria, and induce deficiencies in micronutrients like copper (Cu) and zinc (Zn), ultimately undermining plant and soil health (Bingham and Martin, 1956; Zeng et al., 2022; Zeng et al., 2024). Economically, P is a non-renewable resource essential for food production. Inefficient use of P results in both wasted fertilizer investments and increased vulnerability to volatile global prices, as seen in recent P price spikes that have threatened food security worldwide (Brownlie et al., 2023; Walsh et al., 2023). Furthermore, the costs of mitigating P pollution, such as for water treatment and ecosystem restoration, add to these economic burdens (Sena et al., 2020).

The profound influence of chemical, physical, and biological factors on P solubility in muck soils highlights a critical disconnect. While accurate fertilizer recommendations depend on reliable soil tests, conventional methods are often inadequate. Therefore, this review aims to 1) synthesize current knowledge on the chemical, physical, and biological factors governing P dynamics in muck soils 2) critically evaluate how and why conventional P tests fail, identifying specific research gaps in their calibration and interpretation for these organic systems, and 3) propose a framework for developing management strategies built upon more robust, regionally-calibrated assessment tools. By meeting these objectives, this work provides a focused pathway for improving nutrient management to enhance crop yield while protecting environmental quality.

2 Discrepancy of existing analytical methodologies for assessing plant-available phosphorus in muck soil

Unlike mineral soils for which standardized P analysis procedures exist, there is no universal method for muck soils. Florida adopted Water Soluble Phosphorus (WSP) for vegetable crops and Mehlich-3 for sugarcane (Mylavarapu et al., 2021), while Olsen P was recommended in Ontario (McDonald et al., 2024), Bray-P in Michigan (Warncke, 2025), and WSP in California (UC Agriculture and Natural Resources, 2025). This lack of a single method stems from their chemical diversity, for example, an acidic Histosols where P is held in organic forms is chemically distinct from a long-cultivated, alkaline Histosols in the EAA, where P chemistry is dominated by precipitation with Ca from historical fertilizer applications and bedrock incorporation (Wright et al., 2009). Consequently, a test designed for one environment, such as an acidic extractant, is chemically inappropriate for the other

TABLE 2 Issues with common analytical methodologies for assessing plant-available phosphorus in the muck soils.

Method	Limitation category	Specific limitation	Underlying mechanism of limitation	References
Mehlich-3	Environmental Relevance	Poor indicator of environmental P loss risk, specifically for dissolved reactive P	The Mehlich-3 extracted pool does not provide information about the immediately soluble P fraction, which constitutes the primary environmental risk	Zheng et al. (2015)
	Methodological and Interpretive	Recommendations are often based on flawed linear conversions from older, inappropriate tests with Mehlich-1 rather than extensive field tests in muck soil	Using simple mathematical conversions fails to account for the differences in chemical pools extracted by Mehlich-3 versus Mehlich-1, leading to analytically inconsistent and potentially inaccurate fertilizer recommendations	Mylavarapu et al. (2014), Rodriguez et al. (2024)
WSP	Agronomic Relevance	Fails to account for the substantial P supply from the mineralization of the vast organic P pool throughout the growing season, particularly for muck soil	WSP ignores the P that is released over time by microbial decomposition of organic matter, a critical pathway in muck soils	Zehetner et al. (2018)
		Does not simulate plant-driven P mobilization mechanisms, such as rhizosphere acidification	Plants are not passive absorbers. Plants actively exude compounds to acquire nutrients. WSP is a passive extraction that does not capture this biological component of nutrient availability	
	Physical and Analytical	High water holding capacity of muck soil can cause the soil to absorb the entire extracting solution	The unique physical properties of muck soils (high porosity, low bulk density) interfere with standard lab procedures	Caron et al. (2015)
		The soil-to-water use ratio for extraction varies in the laboratory	This difference in soil-to-water ratio makes inter-laboratory comparisons difficult	Roswall et al. (2021)
Olsen P	Agronomic Relevance	Fails to measure the P supplied by the mineralization of the organic P pool	Similar to the WSP test, the Olsen test is a chemical extraction that does not account for the biological release of P from organic matter over time	Zheng et al. (2015)
	Analytical	Highly susceptible to colorimetric interference from dissolved organic matter (DOM) present in muck soil extracts	The dark-colored DOM chelates or complexes with the molybdenum reagent used for P detection. This reduces the reagent availability to react with phosphate, causing incomplete color development and a significant underestimation of the actual P concentration	Kowalenko and Babuin (2007)
H3A-P	Chemical	Reduced extraction efficiency in high pH (>7.7) calcareous soils	In soils with high pH and free calcium carbonate, these acids are neutralized and buffered, rendering them ineffective at dissolving stable calcium-phosphate minerals	Haney et al. (2017)
FeO-P	Methodological	Lack of standardized procedures for the preparation of the iron-oxide-coated paper and for the extraction process itself	The P-sorbing capacity of the strip is susceptible to its preparation. Minor variations in protocol between labs can significantly alter the amount of P extracted, leading to poor reproducibility and comparability of results	Chardon et al. (1996)

environment. Given the limitations of purely chemical extractions, a comprehensive approach to P management in organic soil should also include assessing soil enzymatic activities and microbial communities. Organic agriculture significantly enhances microbial biomass and enzymatic activity, and these biological shifts are directly linked to improved soil quality and changes in P levels (Durrer et al., 2021; Lori et al., 2017). Therefore, monitoring both biological and chemical soil properties is essential for optimizing P dynamics in organic systems.

3 Issues with common analytical methodologies

The unique physical, chemical, and biological characteristics of muck soils present significant challenges for routine P tests, leading to a disconnect between test results, crop needs, and environmental risk. Although numerous P extraction methods exist, each possesses notable limitations in these systems (Table 2). For instance, the University of Florida's Institute of Food and Agricultural Sciences (UF/IFAS) employs a Mehlich-3 recommendation that is a linear conversion of the older Mehlich-1 test, a method that likely underestimates crop P needs (Mylavarapu et al., 2014). This linear conversion does not account for differences in soil mineralogy or organic matter content (Rodriguez et al., 2024). Similarly, other analyses, such as the WSP and Olsen P tests, often fail to predict plant-available P in muck soils accurately.

These analytical inconsistencies arise because P cycling in organic soils is dominated by biological processes, unlike in mineral soils, where it is driven by geochemistry (Cross and Schlesinger, 2001; Pistocchi et al., 2018). In muck soils, a significant portion of P exists in organic forms (Audette et al., 2018), and the high organic matter content can neutralize acidic extractants, such as Mehlich-1 and 3, thereby compromising the analysis (Mylavarapu et al., 2014). Therefore, instead of seeking a single universal index, research should focus on developing site-specific, validated recommendations and regionally calibrated mechanistic tools. A robust P risk index for Histosols must integrate targeted chemical extraction with key soil properties that govern P mobility, such as organic matter content, pH, and the concentrations of P-binding elements (e.g., Fe, Al, and Ca). For example, in some areas of muck soil, Mehlich-3 extractable Fe played a more significant role in P retention than Mehlich-3 extractable Al, leading one research group to apply a statistically determined multiplier of five to the Fe value to better account for its role when calculating a Phosphorus Saturation Ratio (PSR) (Gué et al., 2007). Other researchers have followed a similar approach to calculate degrees of PSR (Guérin et al., 2011; Leblanc et al., 2013). Other studies, such as those in Brazilian Histosols, used a different index calculated with a Mehlich-1 extractant and no Fe multiplier to determine degrees of PSR (Mikosik et al., 2024). Another study suggested that PSR in wetland soil is unaffected by the amount of organic matter, and P solubility is regulated by Fe and Al (Nair, 2014). PSR is the molar ratio of extractable P to the sum of extractable Fe and Al. The PSR is used as a threshold-based indicator of soil phosphorus loss risk in many systems (Nair and Harris, 2014). These examples underscore the necessity of validating P risk indices based on local soil conditions rather than pursuing a single universal standard.

4 Phosphorus management in muck soil: recommendations

Effective P management in muck soils requires careful consideration of their unique biogeochemical properties. Management strategies must be carefully tailored to maximize crop yield while minimizing environmental P loss. Pre-season soil testing, using tools such as the Phosphorus Saturation Index (PSI), can inform fertilizer decisions by indicating the soil's potential for phosphorus (P) loss. The PSI is a sorption-derived index, derived from a single-point or isotherm approach, used to estimate a soil's P sorption capacity and degree of saturation (de Campos et al., 2016). Fertilizer applications should be avoided when index values are above established threshold values. To maximize uptake efficiency, P applications should be synchronized with crop demand, particularly during early growth stages. In-season monitoring via plant tissue analysis is also a practical tool that provides direct information on the crop's nutritional status and supports corrective, targeted fertilization only when deficiencies are confirmed (Silveira, 2014). Once the correct P rate is determined, the application method strongly affects its efficiency, especially in high-fixation soils. For instance, banding fertilizer increases early crop access to applied P and improves its use efficiency relative to broadcast placement (Hochmuth et al., 2014). It is also important to note that excessive application of P can negatively affect the uptake of other essential nutrients, such as Cu, Fe, Mn, S, and Zn (Safaya, 1976; Yu et al., 2020; Assefa et al., 2021; Yang et al., 2024). Achieving efficient phosphorus utilization requires an integrated approach that encompasses the following key strategies.

4.1 Strategy to adjust the soil chemical properties

The specific chemistry of the soil dictates the appropriate management response. For example, in muck soils overlying limestone bedrock that have high Ca content and high pH, P tends to precipitate as less soluble calcium phosphates. The drainage needed for agricultural production initiates subsidence, which can alter mineral inputs and surface chemistry, ultimately increasing soil pH. The abundant Ca interacts with phosphate ions to form insoluble calcium phosphate minerals, often rendering typical fertilizer rates insufficient for optimal crop growth (Naeem et al., 2013). This is particularly important for muck soil, as it exhibits significantly variable P retention capacities, which play a key role in determining P mobility. Soils with a low P retention capacity pose a higher risk of nutrient loss into surrounding ecosystems (Wright et al., 2009; Kedir et al., 2022). In these cases, management can involve using acid-forming fertilizers or applying elemental sulfur (S) to lower the soil pH (Orem, 2007; Wright et al., 2009; Hochmuth and Hanlon, 2016; Hochmuth et al., 2025). In contrast, acidic muck soils with high Fe and Al content can strongly adsorb P to oxides and hydroxides, making it unavailable. For these soils, liming to raise the pH to a range of 6.0–7.0 can increase P availability (Reddy and DeLaune, 2008; McCray, 2022). Soils that lack significant P-retaining minerals, applied P remains highly soluble, and application rates should not exceed crop nutrient requirements to prevent losses (Harris et al., 2010).

4.2 Soil management and conservation strategies

Beyond fertilization and soil physical-chemical techniques, broader conservation practices are essential for maintaining soil and its associated P in the field. This includes adopting practices like cover cropping, precision land leveling, and conservation tillage to minimize erosion from wind and water (Sharpley et al., 2013). Adding biochar can also improve P availability depending on feedstock, pyrolysis temperature, and application rate (Novak et al., 2014; Glaser and Lehr, 2019; Freitas et al., 2020). Such integrated practices that improve fertilizer uptake efficiency are both economically beneficial and environmentally protective by minimizing residual P accumulation in the soil (Doydora et al., 2020).

4.3 Statistical frameworks for P application determination

A statistical framework can further refine environmental P management. This approach moves beyond simple linear models to more accurately reflect the non-linear nature of crop yield response to nutrient inputs. The primary agronomic benefit is the prevention of over-fertilization, which provides clear economic advantages by eliminating unnecessary fertilizer expenditures that offer no additional yield. Research has established several location-specific change points for muck soils. For instance, in the Wasda Muck of North Carolina, a Mehlich-3 P threshold of 115 mg kg^{-1} was identified. Exceeding this threshold value led to a tenfold increase in WSP, indicating a heightened risk of P loss (Bond et al., 2006). In muck soils in Ontario, Canada, one study found that exceeding a FeO-P value of 238.6 mg kg^{-1} increased dissolved reactive phosphorus (DRP) loss in subsurface leachate by more than fourfold (Zheng et al., 2015), while another study reported exceeding 233.8 mg kg^{-1} in surface runoff increased DRP loss by nearly twelvefold (Zheng et al., 2014). Studies have found that achieving a profitable crop yield is unlikely when FeO-P values exceed 20 mg kg^{-1} (Sims et al., 2002; Nair, 2024). Beyond 20 mg kg^{-1} of extractable FeO-P, P application would be environmentally detrimental. These bioavailable forms of P extraction could provide more reliable estimates of P requirements. However, the conversion of Mehlich-3 to FeO-P is highly site-specific; therefore, it cannot be accurately represented by a single conversion factor for a given site (Rodriguez et al., 2024).

Muck soils hold large but complex P reserves shaped by organic matter dynamics, Ca interactions, and drainage-induced pH changes. Future research should focus on developing unified, soil-specific P indices, exploring biological P mobilization pathways, and validating site-based thresholds for fertilizer use. A balanced application of P, combined with proper management practices can optimize crop yield while minimizing environmental nutrient losses. P fertilizer use in agriculture should be prohibited when soil tests show no P deficiency, and nutrient bioavailability can be maintained through management practices.

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