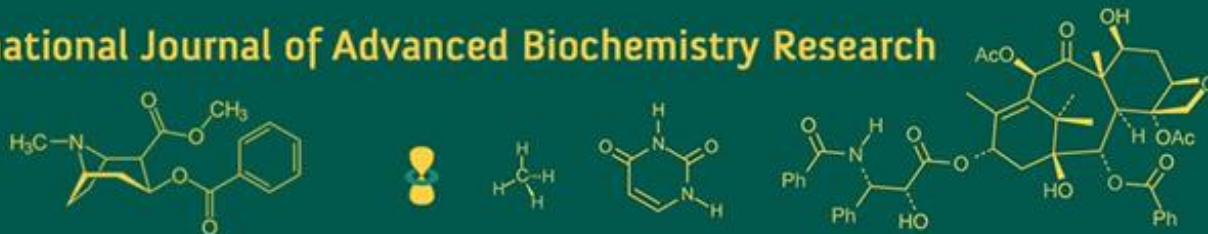


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Exploring the Role and Impact of Organic Acids in Phosphorus Solubilization: Mechanisms, Rhizosphere Processes and Environmental Implications

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Abstract

Phosphorus (P) is a vital macronutrient regulating plant growth and productivity; however, its availability in soils is severely constrained due to fixation into sparingly soluble forms such as calcium (Ca-P), iron (Fe-P) and aluminium phosphates (Al-P). Despite substantial fertilizer inputs, only a small fraction (typically 15–25%) of applied phosphorus is utilized by crops, resulting in low phosphorus use efficiency and accumulation of residual P in soils. This inefficiency necessitates sustainable strategies to mobilize soil-bound phosphorus. Organic acids, predominantly low-molecular-weight carboxylic acids released from plant roots, microorganisms and decomposing organic matter, have emerged as key agents in enhancing phosphorus solubilization. These compounds facilitate P mobilization primarily through proton-induced acidification, metal chelation and ligand exchange reactions that destabilize mineral-phosphate complexes. This review provides a comprehensive and mechanism-oriented synthesis of organic acid-mediated phosphorus solubilization, integrating insights from soil chemistry, rhizosphere processes and microbial interactions. Particular emphasis is placed on the variability in efficiency among different organic acids, their interactions with soil constituents and the factors governing their persistence and effectiveness under field conditions. By critically evaluating existing knowledge and identifying key research gaps, this review advances understanding of how organic acids regulate phosphorus dynamics across diverse soil systems. Overall, harnessing organic acid-driven processes offers a promising pathway to improve phosphorus use efficiency, reduce fertilizer dependency and promote environmentally sustainable nutrient management.

Keywords: Organic acids, Phosphorus solubilization, Rhizosphere, Chelation, Nutrient cycling

1. Introduction

Phosphorus (P) is an indispensable macronutrient that plays a central role in plant metabolism, being a key component of nucleic acids, phospholipids and adenosine triphosphate (ATP), which governs energy transfer in biological systems. It is therefore essential for processes such as cell division, root development, photosynthesis and overall crop productivity (Marschner, 2012) [38]. Despite its critical importance, phosphorus availability remains one of the most limiting factors for crop production across diverse agroecosystems worldwide.

Globally, it is estimated that nearly 40–50% of arable soils are deficient in plant-available phosphorus, particularly in highly weathered tropical soils and calcareous soils of arid and semi-arid regions (Hinsinger, 2001; Vance *et al.*, 2003) [22, 67]. Although large quantities of phosphorus fertilizers are applied annually, only 15–25% of the applied phosphorus is effectively utilized by plants, while the remaining portion becomes immobilized in soil (Holford, 1997; Cordell *et al.*, 2009) [26, 9]. This low phosphorus use efficiency not only increases production costs but also contributes to long-term accumulation of residual phosphorus, raising concerns about environmental sustainability.

The limited availability of phosphorus in soils is primarily attributed to its rapid fixation into insoluble forms. In acidic soils, phosphorus is predominantly fixed as iron (Fe-P) and aluminium phosphates (Al-P), whereas in neutral to alkaline soils, it precipitates as calcium phosphates (Ca-P). Additionally, phosphate ions are strongly adsorbed onto the surfaces of clay minerals and Fe/Al oxides through ligand exchange mechanisms, further reducing their mobility and bioavailability (Sanyal and De Datta, 1991; Hinsinger, 2001) [54, 22]. These physicochemical processes maintain phosphorus in forms that are largely inaccessible to plants, despite its abundance in total soil P pools.

To overcome phosphorus deficiency, the application of chemical fertilizers such as single superphosphate (SSP), diammonium phosphate (DAP) and triple superphosphate (TSP) has been widely adopted. However, the efficiency of these inputs is constrained by rapid fixation reactions in soil, leading to low recovery efficiency and necessitating repeated applications. Moreover, excessive reliance on inorganic fertilizers is associated with economic and environmental challenges, including resource depletion of phosphate rock reserves and increased risk of eutrophication due to phosphorus losses (Cordell *et al.*, 2009; Richardson *et al.*, 2009) [9, 48].

In this context, organic acids have gained considerable attention as natural agents capable of enhancing phosphorus solubilization in soils. Organic acids, particularly low-molecular-weight carboxylic acids such as citric, oxalic, malic and acetic acids, are released into the soil through plant root exudation, microbial metabolism and decomposition of organic matter. These compounds influence phosphorus availability through multiple mechanisms, including rhizosphere acidification, chelation of metal cations (Fe^{3+} , Al^{3+} , Ca^{2+}), ligand exchange reactions and competitive adsorption processes (Jones, 1998; Bolan *et al.*, 1994; Hinsinger, 2001) [31, 6, 22]. As a result, they play a crucial role in mobilizing sparingly soluble phosphorus fractions and enhancing plant uptake.

Despite extensive research on organic acid-mediated phosphorus solubilization, several critical gaps remain. Most studies have focused on controlled laboratory conditions, with limited understanding of the dynamics and efficiency of organic acids under field conditions. Furthermore, the variability in effectiveness among different organic acids, their interactions with diverse soil types and their rapid turnover and adsorption in soils are not yet fully understood. A comprehensive, mechanism-based synthesis that integrates soil chemistry, rhizosphere processes and microbial interactions is therefore needed to better elucidate their role in phosphorus cycling.

This review critically evaluates the role of organic acids in phosphorus solubilization by examining their sources, chemical characteristics and underlying mechanisms in soil systems, along with their implications for improving phosphorus use efficiency and sustainable nutrient management.

4. Soil Phosphorus Chemistry and Constraints

Phosphorus in soils exists in a complex array of inorganic and organic forms that are governed by dynamic chemical equilibria, strongly influencing its availability to plants. Although total soil phosphorus content may be substantial, only a minute fraction is present in plant-available forms, primarily as orthophosphate ions (H_2PO_4^- and HPO_4^{2-}) in the soil solution (Hinsinger, 2001; Schachtman *et al.*, 1998) [22, 56]. The disparity between total and available phosphorus is a fundamental constraint in soil fertility management.

4.1 Forms of Phosphorus in Soil

4.1.1 Inorganic Phosphorus Forms

Inorganic phosphorus constitutes a major portion of total soil P and is predominantly associated with calcium (Ca), iron (Fe) and aluminium (Al), depending on soil pH and mineralogy.

• Calcium-bound phosphorus (Ca-P):

In neutral to alkaline soils, phosphorus is primarily present as calcium phosphates such as dicalcium phosphate, octacalcium phosphate and hydroxyapatite. These forms are relatively stable and exhibit low solubility under high pH conditions (Holford, 1997; Penn and Camberato, 2019) [26, 44].

• Iron-bound phosphorus (Fe-P):

In acidic soils, phosphorus reacts with Fe oxides and hydroxides (*e.g.*, goethite, hematite), forming Fe-P complexes through adsorption and precipitation mechanisms. These compounds are highly reactive and strongly retain phosphate ions (Sanyal and De Datta, 1991; Fink *et al.*, 2016) [54, 11].

• Aluminium-bound phosphorus (Al-P):

Aluminium phosphates dominate in strongly acidic soils and are formed via precipitation and specific adsorption onto Al hydroxides. These forms are often sparingly soluble and contribute significantly to phosphorus fixation (Hinsinger, 2001; Gerard, 2016) [22, 17, 18].

4.1.2 Organic Phosphorus Forms

Organic phosphorus accounts for 20–80% of total soil P, depending on soil type and organic matter content. It includes compounds such as:

- Inositol phosphates (phytate)
- Phospholipids
- Nucleic acids

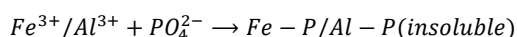
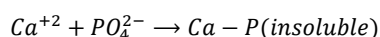
These forms are not directly available to plants and require mineralization through microbial activity to release inorganic phosphate (Condon *et al.*, 2005; Richardson and Simpson, 2011) [8, 50, 51]. The turnover of organic P is therefore closely linked to soil biological processes.

4.2 Mechanisms of Phosphorus Fixation

Phosphorus fixation refers to the transformation of soluble phosphate into less available forms through physicochemical reactions. This process occurs rapidly after fertilizer application and is influenced by soil properties such as pH, mineral composition and clay content.

4.2.1 Precipitation Reactions

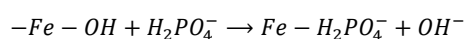
- In alkaline soils:
- In acidic soils:



These precipitation reactions convert soluble phosphorus into sparingly soluble mineral forms, significantly reducing its availability (Holford, 1997; Penn and Camberato, 2019) [26, 44].

4.2.2 Adsorption onto Soil Colloids

Phosphate ions are strongly adsorbed onto clay minerals and Fe/Al oxides via ligand exchange reactions, where phosphate replaces hydroxyl groups on mineral surfaces:



This specific adsorption mechanism leads to strong binding of phosphorus and limits its desorption into soil solution (Hinsinger, 2001; Gerard, 2016) [22, 17, 18].

4.2.3 Occlusion and Aging

Over time, adsorbed phosphorus becomes occluded within mineral structures or diffuses into micropores, forming highly stable and inaccessible forms. This process, often referred to as “aging,” further reduces phosphorus availability and contributes to long-term fixation (Sanyal and De Datta, 1991; Fink *et al.*, 2016) [54, 11].

4.3 Availability of Phosphorus vs Total Phosphorus

A critical aspect of soil phosphorus chemistry is the large disparity between total phosphorus and plant-available phosphorus. While total soil P may range from 200 to 3000 mg kg⁻¹, the concentration of phosphorus in soil solution is typically very low, often less than 0.1 mg L⁻¹ (Schachtman *et al.*, 1998; Shen *et al.*, 2011) [56, 59].

The availability of phosphorus is governed by:

- Soil pH (optimum ~6.0–7.0)
- Mineral composition (Fe/Al oxides, Ca carbonates)
- Organic matter content
- Microbial activity

Moreover, phosphorus exists in a dynamic equilibrium among different soil pools- solution P, labile P and non-labile P- where only the labile fraction contributes directly to plant uptake (Hinsinger *et al.*, 2015) [24]. However, this equilibrium is often slow, limiting the replenishment of solution P during crop demand.

Recent studies highlight that despite long-term fertilizer application, a significant portion of phosphorus accumulates as residual or legacy P, which remains unavailable due to strong fixation mechanisms (Withers *et al.*, 2018; Menezes-Blackburn *et al.*, 2018) [71, 39]. This underscores the importance of mobilizing existing soil phosphorus pools rather than relying solely on external inputs.

4.4 Implications for Phosphorus Management

The strong fixation and low mobility of phosphorus in soils present a major challenge for improving nutrient use efficiency. Understanding the chemical forms and transformation pathways of phosphorus is therefore essential for developing strategies to enhance its availability. In this context, processes that can mobilize fixed phosphorus, such as organic acid-mediated solubilization, play a crucial role in sustainable soil fertility management.

5. Organic Acids in Soil: Classification and Properties

Organic acids (OAs) are a diverse group of carbon-containing compounds characterized by the presence of one or more carboxyl (-COOH) functional groups, which impart acidic properties through proton dissociation. In soils, organic acids play a crucial role in regulating nutrient availability, particularly phosphorus, by influencing mineral dissolution, metal

complexation and rhizosphere chemistry (Jones, 2011; Hinsinger, 2001) [34, 22]. They are continuously introduced into the soil system through plant root exudation, microbial metabolism and decomposition of organic residues, forming a dynamic and reactive component of soil organic matter.

5.1 Classification of Organic Acids

Organic acids in soils are broadly classified into two categories based on their molecular weight, solubility and functional characteristics.

5.1.1 Low Molecular Weight Organic Acids (LMWOAs)

Low molecular weight organic acids are the most biologically active fraction and play a dominant role in phosphorus solubilization. These compounds typically have molecular weights ranging from approximately 46 to a few hundred Daltons and contain one to three carboxyl groups. Common examples include citric, oxalic, malic, succinic, tartaric, acetic and formic acids.

LMWOAs are highly soluble in water and exhibit rapid turnover in soil due to microbial utilization and adsorption onto mineral surfaces. Their small molecular size and high reactivity enable them to interact effectively with soil minerals and metal ions, making them key drivers of nutrient mobilization in the rhizosphere (Strobel, 2001; Jones *et al.*, 2003) [63, 33]. Their concentrations in soil solution are typically low, ranging from micromolar to millimolar levels, but they exert disproportionately large effects on soil chemical processes.

5.1.2 High Molecular Weight Organic Acids (HMWOAs)

High molecular weight organic acids primarily include humic and fulvic acids, which are complex, heterogeneous macromolecules derived from the decomposition of plant and microbial residues. These compounds possess multiple functional groups, including carboxyl, phenolic and hydroxyl groups and exhibit strong metal-binding capacity.

Unlike LMWOAs, HMWOAs are less soluble and more persistent in soils, contributing to long-term nutrient dynamics rather than rapid solubilization processes. Fulvic acids, due to their relatively lower molecular weight and higher solubility compared to humic acids, are more effective in mobilizing phosphorus through chelation and transport processes (Haynes and Mokolobate, 2001; Perminova *et al.*, 2003) [21, 45]. However, their role is generally indirect and slower compared to LMWOAs.

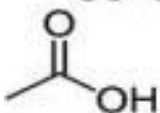
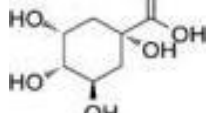
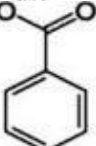
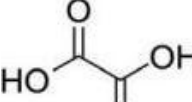
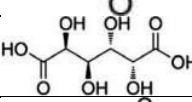
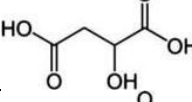
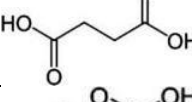
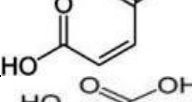
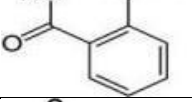
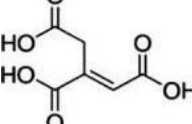
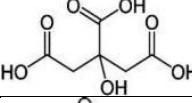
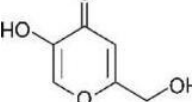
5.2 Chemical Properties of Organic Acids

The effectiveness of organic acids in soil processes is largely determined by their chemical properties, particularly the number and position of carboxyl groups and their acid dissociation constants (pKa) (Table 1).

5.2.1 Carboxyl Functional Groups (-COOH)

The number of carboxyl groups directly influences the ability of organic acids to donate protons and form complexes with metal cations. Organic acids can be categorized as:

Table 1: The chemical characteristics of organic acids

Carboxyl groups	Name (Reagent grade)	weight	Formula	pKa	pH	icture
Monocarboxylic	Acetic acid (99%)	126.07	CH ₃ CO ₂ H	pKa = 4.75	3.93	
	Quinic acid (98%)	192.17	C ₇ H ₁₂ O ₆	pKa = 3.46	3.24	
	Benzoic acid (≥99.5%)	122.12	C ₆ H ₅ CO ₂ H	pKa = 4.204	3.68	
Dicarboxylic	Oxalic acid (99.6%)	126.07	(CO ₂ H) ₂	pKa1 = 1.2pKa2 = 4.2	2.87	
	Mucic acid (97%)	210.14	C ₆ H ₁₀ O ₈	pKa = 2.83	3.31	
	Malic acid (99%)	134.09	C ₄ H ₆ O ₅	pKa1 = 3.51pKa2 = 5.03	3.35	
	Succinic acid (≥99.5%)	162.05	C ₄ H ₆ O ₄	pKa1 = 4.21pKa2 = 5.60	3.40	
	Maleic acid (99%)	116.08	C ₄ H ₄ O ₄	pKa1 = 2.00pKa2 = 6.26	3.06	
	Phthalic acid (≥99.5%)	166.13	C ₈ H ₆ O ₄	pKa1 = 2.76pKa2 = 4.92	3.16	
Tricarboxylic	Trans-aconitic acid (98%)	174.11	C ₆ H ₆ O ₆	pKa1 = 2.80pKa2 = 4.46	3.15	
	Citric acid (99.9%)	192.13	C ₆ H ₈ O ₇	pKa1 = 3.13pKa2 = 4.76pKa3 = 6.39	3.19	
Enol	Kojic acid (≥98.5%)	142.11	C ₆ H ₆ O ₄	pKa = 9.40	5.62	

- Monocarboxylic acids (*e.g.*, acetic, formic acid)
- Dicarboxylic acids (*e.g.*, oxalic, malic, succinic acid)
- Tricarboxylic acids (*e.g.*, citric acid)

An increase in the number of carboxyl groups enhances both proton release and chelation capacity, thereby improving their effectiveness in phosphorus solubilization (Bolan *et al.*, 1994; Jones, 1998) [6, 31].

5.2.2 Acid Dissociation Constant (pKa)

The pKa value of an organic acid determines its degree of dissociation and proton release under given soil pH conditions.

Organic acids with lower pKa values dissociate more readily, releasing protons that contribute to rhizosphere acidification. For example:

- Citric acid: multiple pKa values (~3.1, 4.8, 6.4)
- Oxalic acid: strong acid with low pKa (~1.2, 4.2)

These properties influence their capacity to lower soil pH and dissolve phosphate minerals (Jones, 1998; Hinsinger, 2001) [31, 22].

5.3 Stability, Persistence and Reactivity in Soil

Organic acids are highly dynamic in soil environments and exhibit rapid turnover due to biological and physicochemical processes.

- **Microbial degradation:**

A significant proportion of LMWOAs is rapidly metabolized by soil microorganisms, often within hours of release, limiting their persistence in soil solution (Jones, 1998; Fujii *et al.*, 2013) [31, 15, 16].

A large proportion of LMWOAs is rapidly consumed by soil microorganisms, often within minutes to hours after release (Jones, *et al.*, 2003) [33].

- **Adsorption onto soil minerals:**

Organic acids are strongly adsorbed onto clay minerals and Fe/Al oxides, reducing their mobility and availability for phosphorus solubilization (Andrade *et al.*, 2013) [2].

- **Complexation reactions:**

Their reactivity with metal ions (Fe^{3+} , Al^{3+} , Ca^{2+}) leads to the formation of stable $^{++}$ organo-metal complexes, which can either enhance or limit phosphorus mobilization depending on environmental conditions (Gerard, 2016) [17, 18].

The balance between these processes determines the effective concentration and functional lifespan of organic acids in the rhizosphere.

5.4 Relative Efficiency of Organic Acids in Phosphorus Solubilization

The effectiveness of organic acids in mobilizing phosphorus is strongly influenced by their molecular structure and functional group composition. A widely recognized trend is:

Tricarboxylic acids > Dicarboxylic acids > Monocarboxylic acids

Tricarboxylic acids, such as citric acid, exhibit the highest efficiency due to:

- Greater proton donation capacity
- Stronger chelation with metal cations
- Higher stability constants

Dicarboxylic acids (*e.g.*, oxalic acid) are moderately effective, particularly in Fe- and Al-rich soils, while monocarboxylic acids (*e.g.*, acetic acid) are relatively less effective due to limited chelation ability (Bolan *et al.*, 1994; Strobel, 2001; Penn and Camberato, 2019) [6, 63, 44].

5.5 Implications for Soil Phosphorus Dynamics

The classification and chemical properties of organic acids determine their role in regulating phosphorus availability in soils. Their ability to modify rhizosphere chemistry, interact with soil minerals and influence nutrient cycling highlights their importance as natural mediators of phosphorus solubilization. However, their effectiveness is constrained by rapid turnover and environmental variability, necessitating a deeper understanding of their behavior under field conditions.

6. Sources and Dynamics of Organic Acids in Soil

Organic acids in soils constitute a highly dynamic and reactive pool of low- and highmolecular-weight compounds derived from multiple biotic and abiotic sources. Their production, release, transformation and persistence in the soil environment

are governed by complex interactions among plant roots, soil microorganisms and organic matter decomposition processes. These dynamics critically regulate their effectiveness in mobilizing phosphorus and other nutrients in the rhizosphere (Jones, 1998; Hinsinger *et al.*, 2015) [31, 24].

6.1 Root-Derived Organic Acids

Plant roots represent one of the primary sources of organic acids in soil through the process of rhizodeposition. Root exudates comprise a wide range of compounds, including sugars, amino acids, phenolics and organic acids, of which low-molecular-weight organic acids (LMWOAs) such as citrate, malate, oxalate and fumarate are particularly important for phosphorus mobilization (Marschner, 2012; Badri and Vivanco, 2009) [38, 3]. The release of organic acids by roots is highly regulated and often induced under nutrient stress conditions, particularly phosphorus deficiency. Plants respond to low P availability by increasing the exudation of carboxylates into the rhizosphere, which enhances the solubilization of sparingly soluble phosphorus forms (Hinsinger, 2001; Neumann and Römheld, 1999) [22, 41]. For instance, species such as white lupin (*Lupinus albus*) are known to exude large amounts of citrate under P-deficient conditions, leading to significant mobilization of soil P (Lambers *et al.*, 2006) [36].

Mechanistically, root exudation occurs via both active and passive processes. Active transport involves ATP-dependent secretion through membrane transporters, whereas passive diffusion is governed by concentration gradients and membrane permeability (Badri and Vivanco, 2009) [3]. Additionally, anion channels facilitate the release of negatively charged organic acid ions, driven by electrochemical gradients established through proton extrusion by H^+ -ATPases⁺ (Neumann and Römheld, 1999) [41].

Root-derived organic acid exudation is influenced by several environmental factors, including soil pH, nutrient availability, moisture, temperature and plant genotype. Acidic conditions and phosphorus deficiency generally enhance exudation rates, while environmental stresses such as drought and metal toxicity (*e.g.*, Al^{3+} stress) can also stimulate organic acid release as an⁺ adaptive response (Jones, 1998; Dakora and Phillips, 2002) [31, 10].

6.2 Microbial Production of Organic Acids

Soil microorganisms constitute another major source of organic acids, producing a diverse range of compounds as metabolic by-products during the decomposition of organic substrates and nutrient acquisition processes. Phosphate-solubilizing microorganisms (PSMs), including bacteria such as *Bacillus*, *Pseudomonas*, *Rhizobium* and fungi such as *Aspergillus* and *Penicillium*, are particularly important in this context (Rodríguez and Fraga, 1999; Richardson and Simpson, 2011) [52, 50, 51].

Microbial production of organic acids occurs primarily through pathways such as glycolysis, the tricarboxylic acid (TCA) cycle and oxidative fermentation. For example, gluconic acid is produced via the direct oxidation of glucose, while citric and oxalic acids are generated through TCA cycle intermediates (Jones *et al.*, 2003) [33]. These organic acids contribute to phosphorus solubilization by lowering pH and chelating metal cations.

Microbial activity in the rhizosphere is closely linked to root exudation, as plants supply carbon substrates that stimulate microbial proliferation and metabolic activity. This results in a synergistic interaction between plant roots and microorganisms,

enhancing the production of organic acids and nutrient mobilization (Hinsinger *et al.*, 2015) ^[24]. Mycorrhizal fungi further modify organic acid dynamics by influencing root exudation patterns and extending the effective root surface area. Environmental factors such as soil moisture, temperature, aeration and substrate availability strongly influence microbial production of organic acids. Optimal microbial activity generally occurs under moderate moisture and temperature conditions, whereas extreme conditions may suppress microbial metabolism and reduce organic acid production (Frey-Klett *et al.*, 2007) ^[14].

6.3 Organic Matter Decomposition as a Source of Organic Acids

The decomposition of plant residues and soil organic matter is a significant source of both low and high-molecular-weight organic acids. During decomposition, microbial enzymatic activity breaks down complex organic compounds into simpler molecules, including organic acids such as acetic, lactic, citric and various phenolic acids (Haynes and Mokolobate, 2001) ^[21]. Humic substances formed during decomposition, particularly fulvic acids, play an important role in nutrient mobilization

through metal complexation and transport processes. These compounds contribute to long-term soil fertility by influencing phosphorus availability and buffering soil pH (Perminova *et al.*, 2003) ^[45].

The addition of organic amendments, such as compost and crop residues, can significantly increase the concentration of organic acids in soil, thereby enhancing phosphorus solubilization and nutrient cycling (Iyamuremye *et al.*, 1996) ^[29]. However, the composition and effectiveness of organic acids derived from decomposition depend on the type of organic material and environmental conditions. The major sources of organic acids in soil, their typical concentration ranges and their relationships to mobilization of metals are presented in Table 2.

6.4 Environmental Regulation of Organic Acid Dynamics

The production, release and effectiveness of organic acids in soils are strongly regulated by environmental factors:

- Soil pH: Influences dissociation of organic acids and their interaction with soil minerals
- Phosphorus deficiency: Major driver of root exudation

Table 2: Quantities of different soil organic acids from different sources and their relationships to mobilization of metals.

Organic acid	Source	Quantity produced	Presence or absence of metal	Reference
Plant Citric acid	Soybean	4 μ M	Phosphorus	Nwoke <i>et al.</i> (2008) ^[43]
Citric oxalic, malic	Pigeon pea	17 μ M		Veneklaas <i>et al.</i> (2003) ^[68]
	Chickpea	0.01–84 μ M	-	
Citrate	Chickpea	0.001 μ M	Phosphorus	Neumann and Romheld (1999) ^[41]
Malate	Chickpea	0.002 μ M	Phosphorus	
Acetic and lactic acid	Maize	1.5–3.5 μ M	-	Fischer <i>et al.</i> (2010) ^[12]
Malate	Wheat	0.25 μ M	Phosphorus	Neumann and Romheld (1999) ^[41]
Citric, oxalic and tartaric	Cotton	5–5.0 μ M	Aluminium	Hue <i>et al.</i> (1986) ^[28]
Citrate	Tomato	0.13 μ M	Phosphorus	Neumann and Romheld (1999) ^[41]
Malate	Tomato	0.14 μ M	Phosphorus	
Formic and acetic acids	Lupin	58 μ M	-	Veneklaas <i>et al.</i> (2003) ^[68]
Citric acid	Lupin	0.1–0.3 μ M	Aluminium	Mimmo <i>et al.</i> (2008) ^[40]
Fumaric	Lupin	3.3–7.6 μ M	Aluminium	Mimmo <i>et al.</i> (2008) ^[40]
Malonic acid	Lupin	43.3–140 μ M	Aluminium	Mimmo <i>et al.</i> (2008) ^[40]
A-Ketoglutaric acid	Lupin	5.4–7.6 μ M	Aluminium	Mimmo <i>et al.</i> (2008) ^[40]
Citric acid	Lupin	0.1–1000 μ M	-	Van Hees <i>et al.</i> (2002) ^[66] , Sulyok <i>et al.</i> (2005) ^[65]
Citrate	Lupin	0.02 μ M	Phosphorus	Johnson <i>et al.</i> (1996) ^[30]
Malate	Lupin	0.03 μ M	Phosphorus	Mimmo <i>et al.</i> (2008) ^[40]
Citrate Malate	Lupin	0.02 μ M	Phosphorus	Neumann and Romheld (1999) ^[41]
Citric, acetic, tartaric	Pinus	0.08 μ M	Phosphorus	Blossfeld <i>et al.</i> (2011) ^[5] , Baziramakenga <i>et al.</i> (1995) ^[4]
		Up to 1 μ M	-	
Microbes				
Oxalic acid	Fungus	0.6–2 mM	Lead (Pb)	Fomina <i>et al.</i> (2006) ^[13]
Citric, acetic, formic	Fungus	~5820 μ M	-	Holmström <i>et al.</i> (2005), Vranová <i>et al.</i> (2013)
Citric acid	Lichen	0.1–15 μ M	-	Fujii <i>et al.</i> (2013) ^[15, 16]
Oxalic acid	Bacteria	Up to 3 μ M	-	Ren <i>et al.</i> (2009) ^[47]
Citric acid	Bacteria	0.1–100 μ M	-	Christou <i>et al.</i> (2006) ^[7] , Van Hees <i>et al.</i> (2002) ^[66]
Organic waste				
Citrate, Malate	Rhizosphere	50 μ M	-	Jones <i>et al.</i> (1996) ^[32]
Citric, oxalic acid Citric acid	Rhizosphere	1 mM–80 mM		Strom <i>et al.</i> (2005) ^[64] Strobel (2001) ^[63]
	Rhizosphere	1–50 μ M		Adeleke <i>et al.</i> (2012b) ^[11]
Citric, oxalic, malic acids	Plant and fungi	0.5–3.1 μ M	-	Stevenson and Vance (1989) ^[62]
Citric, oxalic, acetic acids	Plant and bacteria	1–5 μ M		

- Metal toxicity (e.g., Al^{3+}): Stimulates release of chelating organic acids
- Soil moisture and temperature: Regulate microbial activity and decomposition rates
- Soil texture and mineralogy: Affect adsorption and persistence of organic acids

These factors determine the concentration, mobility and reactivity of organic acids in the rhizosphere (Jones, 1998; Hinsinger *et al.*, 2015) [31, 24].

6.5 Turnover, Persistence and Half-Life of Organic Acids

Organic acids are characterized by rapid turnover in soils, which limits their persistence and effective concentration in the rhizosphere.

• Adsorption and immobilization:

Organic acids are strongly adsorbed onto soil colloids, particularly Fe and Al oxides, reducing their availability for phosphorus solubilization (Andrade *et al.*, 2013) [2].

• Half-life:

The half-life of organic acids in soil is typically short, ranging from a few minutes to several hours depending on soil type and environmental conditions (Fujii *et al.*, 2013) [15, 16].

Despite their transient nature, continuous production by plant roots and microorganisms maintains a steady-state concentration in the rhizosphere, enabling sustained influence on phosphorus dynamics.

6.6 Implications for Phosphorus Solubilization

The effectiveness of organic acids in mobilizing phosphorus is determined not only by their chemical properties but also by their sources and dynamic behavior in soil. The interplay between root exudation, microbial production and organic matter decomposition creates a complex but efficient system for phosphorus mobilization. However, rapid turnover and environmental constraints highlight the need for better understanding of their temporal and spatial dynamics under field conditions. The sources, transformation pathways and functional roles of organic acids in soil systems are schematically illustrated in Figure 1.

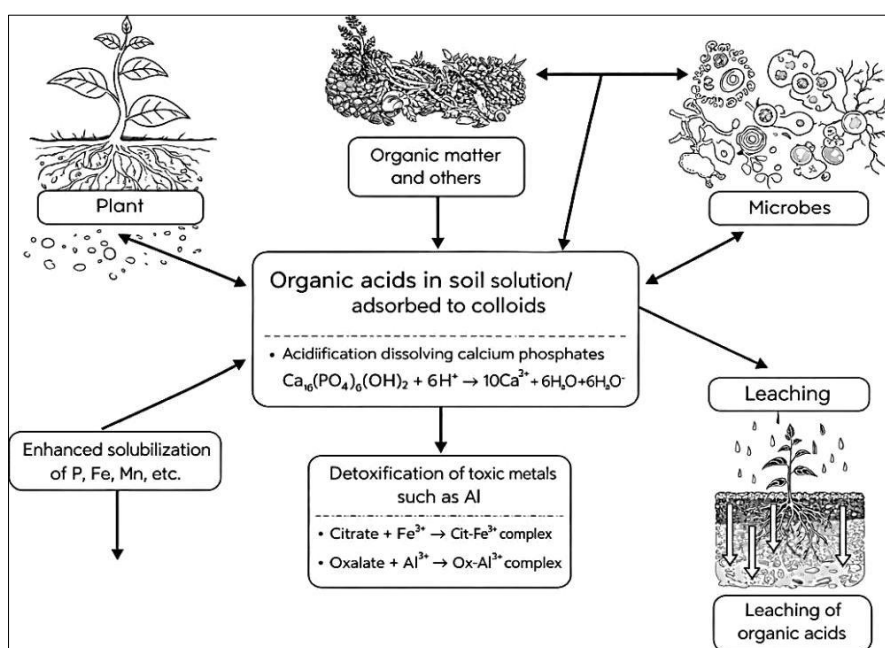


Fig 1: Conceptual model illustrating the sources, dynamics and functional roles of organic acids in soil phosphorus solubilization

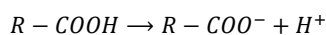
7. Mechanisms of Organic Acid-Mediated Phosphorus Solubilization

Organic acids enhance phosphorus (P) availability in soils through multiple interconnected physicochemical mechanisms that operate simultaneously in the rhizosphere. These mechanisms primarily involve modification of soil pH, complexation of metal cations, displacement of phosphate ions from mineral surfaces and dissolution of P-bearing minerals. The relative importance of each mechanism depends on the type of organic acid, soil properties and environmental conditions (Jones, 1998; Hinsinger, 2001; Penn and Camberato, 2019) [31, 22, 44].

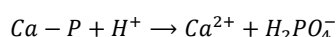
7.1 Proton-Induced Acidification

One of the primary mechanisms of phosphorus solubilization by organic acids is rhizosphere acidification through proton (H^+) release. Organic acids dissociate in soil solution, releasing

protons that lower the local pH and enhance the solubility of sparingly soluble phosphate minerals.



The decrease in pH promotes the dissolution of calcium phosphates in alkaline soils:



This mechanism is particularly important in calcareous and alkaline soils, where phosphorus is predominantly present as Ca-bound forms. Organic acids such as citric, oxalic, malic and acetic acids contribute to this process by releasing protons into the rhizosphere (Bolan *et al.*, 1994; Hinsinger, 2001) [6, 22].

However, in strongly acidic soils, further acidification may have limited benefits or even adverse effects due to increased fixation of phosphorus by Fe and Al oxides. Thus, the

effectiveness of acidification depends strongly on initial soil pH and buffering capacity (Penn and Camberato, 2019) [44].

7.2 Chelation and Complexation

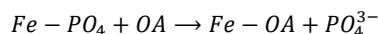
Chelation is a key mechanism by which organic acids enhance phosphorus availability through the formation of stable complexes with metal cations such as Fe^{3+} , Al^{3+} and Ca^{2+} . Organic acids⁺ containing multiple carboxyl groups bind these cations, reducing their interaction with phosphate and thereby releasing bound phosphorus. Metal- OA Metal-OA complex This mechanism is especially effective in acidic soils, where Fe and Al oxides strongly bind phosphate. By chelating Fe^{3+} and Al^{3+} , organic acids such as citric acid (tricarboxylic) and oxalic acid (dicarboxylic) destabilize Fe-P and Al-P complexes, increasing phosphorus solubility (Jones, 1998; Gérard, 2016) [31].

Citric acid is particularly effective due to its three carboxyl groups, which provide strong binding affinity and higher

stability constants with metal ions. Oxalic acid can also form insoluble metal oxalates, indirectly releasing phosphate into the soil solution (Bolan *et al.*, 1994; Penn and Camberato, 2019) [6, 44]. The dissolution of different phosphorus forms (Ca-P, Fe-P and Al-P) mediated by organic acids and microbial activity is illustrated in Figure 2.

7.3 Ligand Exchange Reactions

Ligand exchange is a surface chemical process in which organic acid anions replace phosphate ions adsorbed onto soil mineral surfaces, particularly Fe and Al oxides.



In this mechanism, organic acid anions compete directly with phosphate for adsorption sites, leading to desorption of phosphate into the soil solution. This process is highly significant in highly weathered tropical soils rich in Fe and Al oxides.

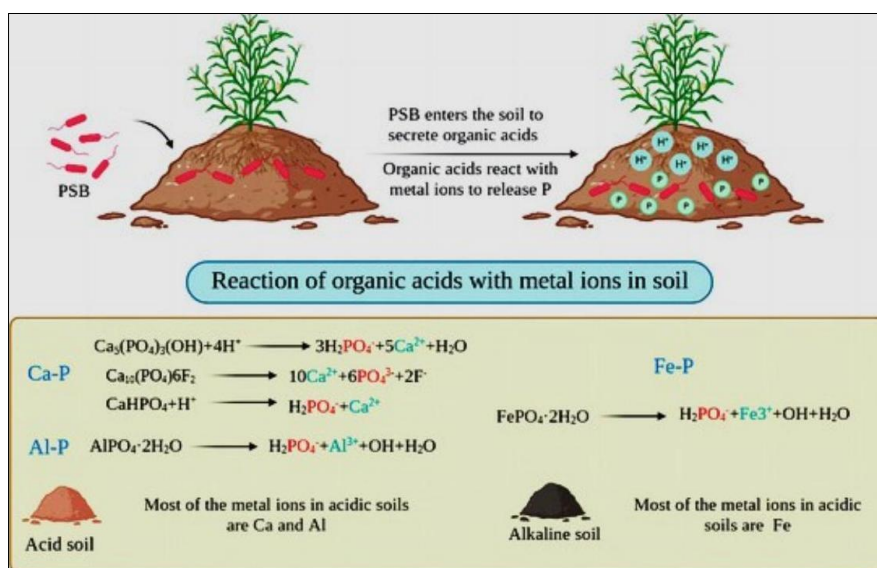


Fig 2: Phosphate-solubilizing bacteria release phosphorus through organic acid-mediated mineral dissolution in soils

Organic acids such as citrate and malate exhibit strong ligand exchange capacity due to their ability to form inner-sphere complexes with metal oxides (Hinsinger, 2001; Gerard, 2016) [22, 17, 18]. The effectiveness of this mechanism depends on the affinity of the organic acid for the mineral surface and its concentration in the rhizosphere.

7.4 Competitive Adsorption

Competitive adsorption involves the competition between organic acid anions and phosphate ions for binding sites on soil colloids. Organic acids occupy adsorption sites on clay minerals and metal oxides, thereby reducing the number of available sites for phosphate fixation.

This mechanism decreases phosphate adsorption and increases its concentration in soil solution, enhancing plant availability. Unlike ligand exchange, which involves direct displacement, competitive adsorption reduces fixation by blocking adsorption sites.

This process is particularly relevant in soils with high clay content and oxide surfaces, where adsorption reactions dominate phosphorus dynamics. Organic acids such as acetic, citric and malic acids have been shown to reduce phosphate

adsorption through this mechanism (Violante *et al.*, 2005; Guppy *et al.*, 2005) [20].

7.5 Mineral Dissolution and Weathering

Organic acids also promote the dissolution of primary and secondary minerals containing phosphorus, contributing to long-term phosphorus release. This mechanism involves both proton attack and complexation of structural metal ions, leading to mineral breakdown.

Mineral-P + OA Dissolved P + Metal-OA

Organic acids enhance the weathering of minerals such as apatite by:

- Lowering pH (proton attack)
- Chelating structural cations (Ca, Fe, Al)
- Increasing mineral surface reactivity

For example, citric and oxalic acids are highly effective in dissolving apatite and other phosphate-bearing minerals due to their strong complexation ability (Jones, 1998; Fink *et al.*, 2016) [31, 11].

This mechanism is particularly important in young soils and mineral-rich environments, where primary minerals serve as a major phosphorus source. It also contributes to long-term phosphorus cycling and pedogenesis.

7.6 Integrated Perspective of Mechanisms

In natural soil systems, these mechanisms rarely operate in isolation. Instead, organic acids simultaneously influence phosphorus availability through a combination of acidification, chelation, ligand exchange and adsorption processes. The dominance of a particular mechanism depends on:

- Soil pH and mineralogy
- Type and concentration of organic acids

- Environmental conditions

Understanding these interacting mechanisms is essential for predicting phosphorus behavior in soils and designing strategies to enhance phosphorus use efficiency. The major mechanisms involved in organic acid-mediated phosphorus solubilization and their soil-specific relevance are summarized in Table 3.

Table 3: Mechanisms of organic acid-mediated phosphorus solubilization

Mechanism	Process description	Soil type relevance	Key organic acids
Acidification	H ⁺ release lowers pH and dissolves Ca-P	Alkaline soils	Citric, acetic
Chelation	Complexation with Fe ³⁺ , Al ³⁺ , Ca ²⁺	Acidic soils	Citric, oxalic
Ligand exchange	Replacement of PO ₄ ³⁻ on mineral surfaces	Fe/Al oxide soils	Citrate, malate
Competitive adsorption	Organic acids occupy adsorption sites	Clay-rich soils	Citric, malic
Mineral dissolution	Weathering of P minerals	Young soils	Citric, oxalic

8. Rhizosphere Processes and Plant Adaptation

The rhizosphere represents a highly dynamic zone of soil influenced by root activity, where intense biochemical interactions regulate nutrient availability and uptake. Under phosphorus (P) deficiency, plants exhibit a range of adaptive responses that modify rhizosphere processes to enhance phosphorus acquisition. Among these, root exudation of organic acids, genotypic variation in exudation patterns and rhizosphere pH modification play pivotal roles in mobilizing soil-bound phosphorus (Hinsinger *et al.*, 2005; Richardson *et al.*, 2011) [25, 49, 50, 51].

8.1 Root Exudation under Phosphorus Stress

Phosphorus deficiency is a major trigger for the enhanced release of organic acids from plant roots. When soil P availability is low, plants actively exude low-molecular-weight organic acids such as citrate, malate and oxalate into the rhizosphere, increasing the solubility of sparingly available phosphorus forms (Neumann and Römheld, 1999; Hinsinger, 2001) [41, 22].

This adaptive response is regulated at both physiological and molecular levels. Under P stress, plants increase the activity of enzymes involved in organic acid synthesis, such as phosphoenolpyruvate carboxylase (PEPC), leading to the accumulation and subsequent exudation of carboxylates (Plaxton and Tran, 2011) [46]. Additionally, the expression of specific transporter proteins, including anion channels and MATE (Multidrug and Toxic Compound Extrusion) transporters, facilitates the release of organic acid anions into the rhizosphere (Ryan *et al.*, 2009) [53].

Certain plant species exhibit specialized adaptations to enhance organic acid exudation. For example, cluster roots in white lupin (*Lupinus albus*) release large quantities of citrate under P deficiency, significantly increasing phosphorus availability in the surrounding soil (Lambers *et al.*, 2006) [36]. Similarly, crops such as maize and wheat exude malate and citrate to mobilize phosphorus from Fe- and Al-bound pools.

8.2 Genotypic Variation in Organic Acid Exudation

The capacity of plants to exude organic acids varies significantly among species and genotypes, influencing their ability to acquire phosphorus from low-P soils. This genotypic variation is an important trait that determines phosphorus use efficiency (PUE) in crops.

Some plant species, particularly those adapted to nutrient-poor environments, exhibit higher rates of organic acid exudation. For instance, legumes such as chickpea and pigeon pea have been shown to release higher concentrations of carboxylates compared to cereals, enhancing their phosphorus acquisition efficiency (Veneklaas *et al.*, 2003) [68]. Similarly, genotypic differences within a species can result in substantial variation in root exudation patterns and P uptake capacity (Richardson *et al.*, 2011) [49, 50, 51].

Genetic regulation of organic acid exudation involves multiple pathways, including those controlling carbon metabolism, transporter activity and stress signaling. Recent studies have highlighted the potential for breeding and selecting crop varieties with enhanced root exudation traits to improve phosphorus acquisition in low-input agricultural systems (Lynch, 2011; Wang *et al.*, 2020) [37, 70].

8.3 Rhizosphere pH Modification

Modification of rhizosphere pH is another critical mechanism by which plants influence phosphorus availability. Root-induced pH changes occur primarily through the release of protons (H⁺) and organic acids, as well as through cation–anion uptake imbalances.⁺

Under phosphorus deficiency, plants often acidify the rhizosphere by increasing proton extrusion via plasma membrane H⁺-ATPases. This acidification enhances the solubility of calcium phosphates in alkaline soils, facilitating phosphorus release (Hinsinger, 2001; Shen *et al.*, 2011) [22, 59]. In contrast, in acidic soils, some plant species may increase rhizosphere pH through uptake of excess cations or release of hydroxyl ions, reducing the fixation of phosphorus by Fe and Al oxides.

Organic acids further contribute to pH modification through their dissociation, releasing protons into the soil solution. The combined effect of proton extrusion and organic acid exudation creates localized pH gradients in the rhizosphere, which significantly influence phosphorus solubility and mobility.

The extent of rhizosphere pH modification depends on plant species, soil buffering capacity and environmental conditions. In highly buffered soils, pH changes may be limited, whereas in low-buffering soils, even small amounts of organic acid release can result in significant shifts in rhizosphere chemistry (Hinsinger *et al.*, 2005) [25].

8.4 Integrated Role of Rhizosphere Processes in Phosphorus Acquisition

Rhizosphere processes operate in a coordinated manner to enhance phosphorus availability and uptake. Root exudation of organic acids, genotypic variation in exudation capacity and pH modification collectively create a microenvironment that favors the mobilization of sparingly soluble phosphorus pools.

These adaptive strategies are particularly important in low-input and nutrient-deficient systems, where plants rely on internal mechanisms rather than external fertilizer inputs to meet their phosphorus requirements. The integration of physiological, biochemical and molecular responses highlights the complexity of plant adaptation to phosphorus stress and underscores the importance of rhizosphere processes in sustainable nutrient management.

9. Microbial Mediation and Synergistic Interactions

Soil microorganisms play a central role in phosphorus (P) mobilization through the production of organic acids and their interactions with plant roots in the rhizosphere. Phosphate-solubilizing microorganisms (PSMs), including bacteria and fungi, enhance phosphorus availability by transforming insoluble P forms into plant-available orthophosphate via biochemical and physicochemical processes (Rodríguez and Fraga, 1999; Richardson and Simpson, 2011) [52, 50, 51].

9.1 Phosphate-Solubilizing Bacteria and Fungi

Phosphate-solubilizing bacteria (PSB) such as *Pseudomonas*, *Bacillus*, *Rhizobium* and *Enterobacter*, along with fungi like *Aspergillus* and *Penicillium*, are among the most efficient microbial agents involved in P solubilization. These organisms release a variety of lowmolecular-weight organic acids that contribute to acidification, chelation and mineral dissolution processes (Rodríguez and Fraga, 1999; Khan *et al.*, 2014) [52, 35]. Microbial solubilization of phosphorus is particularly significant in soils with high levels of Fe-, Al- and Ca-bound P, where direct plant uptake is limited. The effectiveness of PSMs depends on their metabolic activity, population density and interaction with plant roots, which supply carbon substrates necessary for microbial growth (Richardson *et al.*, 2009) [48].

9.2 Organic Acid Production Pathways

Microorganisms produce organic acids through several metabolic pathways, primarily linked to carbon metabolism:

Direct oxidation pathway

- Glucose is oxidized to gluconic acid via glucose dehydrogenase, a key mechanism in bacterial phosphate solubilization.

Tricarboxylic acid (TCA) cycle

- Organic acids such as citric, malic, succinic and oxalic acids are generated as intermediates of central metabolic pathways.

Fermentation pathways:

- Under anaerobic or stress conditions, microbes produce acids such as lactic and acetic acids.

Among these, gluconic acid is one of the most effective acids produced by bacteria due to its strong acidifying capacity, while citric and oxalic acids produced by fungi exhibit high chelation potential (Goldstein, 1995; Jones *et al.*, 2003) [19, 33]. The type and quantity of organic acids produced vary depending on microbial species, substrate availability and environmental conditions.

9.3 Mycorrhizal Interactions and Synergism

Mycorrhizal fungi, particularly arbuscular mycorrhizal fungi (AMF), play a crucial role in enhancing phosphorus acquisition through synergistic interactions with plant roots. These fungi extend the root system via hyphal networks, increasing the effective soil volume explored for nutrient uptake (Smith and Read, 2008) [61].

Mycorrhizal associations influence organic acid dynamics both directly and indirectly:

- Direct effects:** Secretion of organic acids and enzymes that mobilize phosphorus
- Indirect effects:** Modification of root exudation patterns and stimulation of microbial activity in the mycorrhizosphere

The interaction between plants, PSMs and mycorrhizal fungi creates a highly efficient nutrient acquisition system, where:

- Plants provide carbon substrates
- Microbes produce organic acids
- Mycorrhizae enhance nutrient transport

This synergistic relationship significantly improves phosphorus solubilization and uptake, particularly in nutrient-deficient soils (Richardson *et al.*, 2009; Smith *et al.*, 2011) [48, 60].

9.4 Integrated Microbial-Plant Interactions

The combined action of phosphate-solubilizing microorganisms and plant root exudation results in a coordinated system of phosphorus mobilization. Organic acids produced by microbes complement those released by roots, enhancing the overall efficiency of phosphorus solubilization through overlapping mechanisms such as acidification, chelation and ligand exchange.

The effectiveness of these interactions is influenced by environmental factors such as soil pH, moisture, temperature and organic carbon availability, which regulate microbial activity and community composition. Understanding these synergistic processes is essential for developing biologically driven strategies to improve phosphorus use efficiency in sustainable agricultural systems.

10. Factors Influencing Efficiency of Organic Acids

The effectiveness of organic acids (OAs) in mobilizing phosphorus in soils is governed by a complex interplay of soil physicochemical properties, intrinsic characteristics of the organic acids and environmental conditions. These factors determine the extent of organic acid dissociation, interaction with soil minerals, persistence in the rhizosphere and ultimately their capacity to solubilize phosphorus (Hinsinger, 2001; Penn and Camberato, 2019) [22, 44].

10.1 Soil Factors

10.1.1 Soil pH

Soil pH is one of the most critical factors influencing the behavior and effectiveness of organic acids. It controls both the dissociation of organic acids and the speciation of phosphorus in soil.

- In alkaline soils, organic acids enhance phosphorus solubilization primarily through proton-induced acidification, which dissolves calcium phosphates.
- In acidic soils, the role of organic acids shifts toward chelation of Fe³ and Al³⁺, reducing their ability to bind phosphate.

The degree of dissociation of organic acids increases with increasing pH relative to their pK_a values, influencing their ability to form complexes with metal ions. However, strong buffering capacity in some soils may limit pH changes induced by organic acids (Hinsinger, 2001; Gérard, 2016) ^[22].

10.1.2 Clay Content and Mineralogy

Clay minerals significantly affect the adsorption and mobility of organic acids and phosphate ions. Soils with high clay content provide a large surface area for adsorption, which can reduce the effective concentration of organic acids in soil solution.

- High clay soils: Greater adsorption of OAs → reduced availability for P solubilization
- Low clay soils: Higher mobility of OAs → enhanced effectiveness

Additionally, clay mineral type (*e.g.*, kaolinite vs smectite) influences the strength of adsorption and interaction with organic acids (Jones *et al.*, 2003) ^[33].

10.1.3 Iron and Aluminium Oxides

Fe and Al oxides play a dominant role in phosphorus fixation in highly weathered soils. These oxides provide reactive surfaces for phosphate adsorption through ligand exchange mechanisms. Organic acids interact strongly with Fe/Al oxides by:

- Competing for adsorption sites
- Forming stable metal–organic complexes
- Inducing desorption of phosphate

The effectiveness of organic acids is therefore higher in soils rich in Fe and Al oxides, particularly when strong chelating agents such as citrate are present (Gérard, 2016; Fink *et al.*, 2016) ^[11].

10.2 Organic Acid Properties

10.2.1 Number of Carboxyl Groups (–COOH)

The number of carboxyl functional groups directly determines the proton donation and metalbinding capacity of organic acids.

- Tricarboxylic acids (*e.g.*, citric acid): High proton release and strong chelation
- Dicarboxylic acids (*e.g.*, oxalic acid): Moderate effectiveness
- Monocarboxylic acids (*e.g.*, acetic acid): Limited effect

A greater number of –COOH groups enhances both acidification and complexation, making such acids more effective in mobilizing phosphorus (Bolan *et al.*, 1994; Jones, 1998) ^[6, 31].

10.2.2 Stability Constants and Complexation Strength

The stability constant (K) of metal–organic complexes determines the strength and persistence of chelation reactions.

- Organic acids with higher stability constants form stronger complexes with Fe³⁺, Al³⁺ and Ca²⁺
- This reduces metal–phosphate interactions and promotes phosphorus release

For example, citrate forms highly stable complexes with Fe and Al, making it one of the most effective organic acids for phosphorus solubilization (Gérard, 2016; Penn and Camberato, 2019) ^[44].

However, excessively strong complexation may sometimes reduce phosphorus availability if metals are immobilized in

stable complexes without releasing phosphate, highlighting the need for balanced interactions.

10.3 Environmental Factors

10.3.1 Temperature

Temperature influences both microbial activity and the kinetics of chemical reactions involving organic acids.

- Higher temperatures enhance microbial production of organic acids and increase reaction rates
- However, they also accelerate microbial degradation of organic acids, reducing their persistence

Thus, temperature has a dual effect, influencing both production and turnover of organic acids (Fujii *et al.*, 2013) ^[15, 16].

10.3.2 Soil Moisture

Soil moisture regulates microbial activity, diffusion of organic acids and their interaction with soil particles.

- Optimal moisture conditions: Promote microbial activity and organic acid production
- Low moisture (drought): Reduces microbial activity and OA production
- Excess moisture: May lead to leaching losses or anaerobic conditions altering microbial pathways

Moisture also affects the diffusion of organic acids in soil solution, influencing their contact with phosphate minerals (Jones *et al.*, 2003; Hinsinger *et al.*, 2015) ^[33, 24].

10.4 Integrated Influence of Factors

The efficiency of organic acids in phosphorus solubilization is not determined by a single factor but by the combined effects of soil properties, organic acid chemistry and environmental conditions. For instance, a highly effective organic acid such as citric acid may exhibit reduced performance in soils with high adsorption capacity or rapid microbial degradation.

Understanding these interacting factors is essential for predicting the behavior of organic acids under field conditions and for optimizing their role in sustainable phosphorus management.

The key factors influencing the efficiency of organic acids in phosphorus solubilization are summarized in Table 4.

Table 4: Factors influencing the efficiency of organic acids in P solubilization

Category	Factor	Influence
Soil factors	pH	Controls OA dissociation and P form
	Clay content	Adsorption reduces OA availability
	Fe/Al oxides	Increases need for chelation
OA properties	COOH groups	More groups increase efficiency
	Stability constants	Strong complexes enhance P release
Environmental	Temperature	↑ production but ↑ degradation
	Moisture	Controls microbial activity

11. Agronomic Implications

The role of organic acids in mobilizing soil-bound phosphorus has significant implications for improving nutrient use efficiency and sustainable crop production. By enhancing the solubility of sparingly available phosphorus forms, organic acids increase the pool of plant-available P in the rhizosphere, thereby improving phosphorus use efficiency (PUE).

11.1 Improved Phosphorus Use Efficiency

Organic acid-mediated mechanisms such as acidification, chelation and ligand exchange facilitate the transformation of non-labile phosphorus into plant-available forms. This enhances the recovery of both native and applied phosphorus, leading to higher P uptake efficiency by crops. Studies have shown that increased root exudation of organic acids under P-deficient conditions significantly improves phosphorus acquisition in crops such as maize, wheat and legumes (Hinsinger, 2001; Richardson *et al.*, 2011) [22, 49, 50, 51].

11.2 Reduced Fertilizer Input

By mobilizing residual and fixed phosphorus in soils, organic acids reduce the dependence on external phosphorus fertilizer inputs. This is particularly important in agricultural systems with accumulated “legacy phosphorus,” where large quantities of applied P remain unavailable due to fixation. The enhanced utilization of these existing P pools can improve fertilizer efficiency and contribute to more sustainable nutrient management (Withers *et al.*, 2018; Menezes-Blackburn *et al.*, 2018) [71, 39].

11.3 Enhanced Crop Productivity

Improved phosphorus availability resulting from organic acid activity directly translates into better root development, biomass accumulation and crop yield. Enhanced P nutrition supports critical physiological processes such as energy transfer, photosynthesis and nutrient transport, ultimately leading to increased productivity. Crops with higher organic acid exudation capacity have been consistently associated with improved growth performance under low-P conditions (Lambers *et al.*, 2006; Shen *et al.*, 2011) [36, 59].

11.4 Implications for Sustainable Agriculture

The integration of organic acid-mediated processes into nutrient management strategies offers a viable pathway to enhance phosphorus efficiency while minimizing environmental impacts. By reducing fertilizer inputs and improving nutrient recovery, these processes contribute to the development of sustainable and resource-efficient agricultural systems.

12. Environmental Implications

Organic acid-mediated phosphorus (P) solubilization has important environmental implications, particularly in improving nutrient efficiency while minimizing phosphorus losses and associated ecological risks. By enhancing the mobilization and uptake of soil-bound phosphorus, organic acids contribute to more efficient nutrient cycling and reduced environmental degradation.

12.1 Reduced Phosphorus Runoff and Losses

Improved phosphorus availability in the rhizosphere through organic acid activity increases plant uptake efficiency, thereby reducing the accumulation of excess phosphorus in soil. This minimizes the risk of phosphorus loss through surface runoff and erosion, which are major pathways of nutrient transport from agricultural fields to water bodies (Sharpley *et al.*, 2013; Withers *et al.*, 2018) [58, 71].

By facilitating the utilization of both applied and residual phosphorus, organic acids help maintain lower concentrations of labile phosphorus in soil solution, reducing the potential for off-site movement. This is particularly important in intensively managed agricultural systems where phosphorus buildup can lead to environmental contamination.

12.2 Mitigation of Eutrophication

Phosphorus is a key driver of eutrophication in aquatic ecosystems, leading to excessive algal growth, oxygen depletion and deterioration of water quality. Enhancing phosphorus use efficiency through organic acid-mediated processes reduces the need for excessive fertilizer application and limits phosphorus losses to surface waters.

By promoting *in situ* utilization of phosphorus within the soil–plant system, organic acids indirectly contribute to controlling eutrophication risks. Efficient recycling and mobilization of soil phosphorus reduce the likelihood of nutrient enrichment in adjacent aquatic ecosystems (Cordell *et al.*, 2009; Withers *et al.*, 2018) [9, 71].

12.3 Improvement of Soil Health

Organic acids play a significant role in maintaining soil health by influencing chemical, biological and physical processes within the soil system. Their contribution includes:

- Enhanced nutrient cycling: Mobilization of phosphorus and other micronutrients
- Stimulation of microbial activity: Organic acids serve as carbon substrates for soil microorganisms
- Improved soil structure: Interaction with soil minerals and organic matter enhances aggregation

Additionally, organic acids can detoxify harmful metal ions such as Al^{3+} through chelation, thereby improving root growth and microbial activity in acidic soils (Haynes and Mokolobate, 2001; Hinsinger *et al.*, 2015) [21, 24].

12.4 Environmental Sustainability Perspective

The role of organic acids in regulating phosphorus dynamics aligns with the principles of sustainable agriculture by promoting efficient nutrient use and reducing environmental externalities. Their integration into nutrient management strategies supports the transition toward environmentally sound agricultural systems with lower reliance on external inputs and reduced ecological footprint.

13. Critical Analysis

Organic acids have been widely recognized as effective agents for phosphorus (P) solubilization; however, their efficiency varies significantly depending on their chemical characteristics and soil conditions. Among the various organic acids, citric acid is consistently reported as the most effective in mobilizing phosphorus. This superior performance is primarily attributed to its tricarboxylic structure, which provides multiple binding sites for metal cations such as Fe^{3+} , Al^{3+} and Ca^{2+} . The high number of carboxyl groups enhances both proton release and chelation capacity, resulting in stronger destabilization of metal–phosphate complexes and increased phosphorus solubility (Bolan *et al.*, 1994; Jones, 1998; Penn and Camberato, 2019) [6, 31, 44]. In addition, citric acid exhibits higher stability constants with metal ions compared to di- and monocarboxylic acids, further improving its effectiveness in diverse soil systems.

However, despite the well-established benefits of organic acids under controlled conditions, their performance in field environments is often inconsistent. One of the major limitations is the rapid degradation of organic acids in soil due to intense microbial activity. Lowmolecular-weight organic acids are readily utilized as carbon sources by soil microorganisms, resulting in very short residence times—often ranging from

minutes to a few hours (Jones and Brassington, 1998; Fujii *et al.*, 2013) ^[31, 15, 16]. This rapid turnover significantly reduces their effective concentration in the rhizosphere, limiting their sustained impact on phosphorus solubilization.

Despite these advantages, the strong adsorption of organic acids onto soil colloids, particularly Fe and Al oxides, further constrains their availability. Adsorption processes can immobilize organic acids shortly after their release, reducing their mobility and interaction with phosphate minerals (Andrade *et al.*, 2013; Gérard, 2016) ^[2]. In highly weathered soils with high oxide content, this limitation becomes more pronounced, thereby diminishing the efficiency of organic acid-mediated mechanisms.

Another critical aspect is the soil-specific response of organic acids, which determines their overall effectiveness. In alkaline soils, organic acids are generally effective due to their ability to dissolve Ca-bound phosphorus through acidification. In contrast, in acidic soils, their role is largely dependent on chelation of Fe and Al, which may not always result in significant increases in plant-available phosphorus due to re-adsorption or precipitation reactions. Moreover, in soils with high buffering capacity, changes in rhizosphere pH induced by organic acids may be minimal, limiting their solubilization potential (Hinsinger, 2001; Penn and Camberato, 2019) ^[22, 44]. Furthermore, the concentration of organic acids in natural soil systems is typically low, often in the micromolar range, raising questions about whether such concentrations are sufficient to induce substantial phosphorus mobilization under field conditions. Laboratory studies often employ higher concentrations of organic acids, which may overestimate their effectiveness compared to real soil environments.

However, it is important to recognize that organic acids rarely act in isolation in natural systems. Their combined effects with root exudation, microbial activity and rhizosphere processes can create localized conditions that enhance phosphorus availability beyond what would be expected from individual mechanisms. This highlights the importance of considering integrated soil-plant-microbe interactions rather than evaluating organic acids as standalone agents.

Overall, while organic acids represent a powerful mechanism for phosphorus mobilization, their effectiveness is constrained by rapid degradation, adsorption and soil-specific factors. A critical understanding of these limitations is essential for translating laboratory findings into practical field applications and for developing strategies that optimize their role in sustainable phosphorus management.

14. Knowledge Gaps and Future Perspectives

Despite extensive research on organic acid-mediated phosphorus (P) solubilization, several critical knowledge gaps remain that limit the translation of laboratory findings into practical field applications. Addressing these gaps is essential for advancing the role of organic acids in sustainable nutrient management.

14.1 Lack of Field-Scale Validation

Most studies on organic acid-mediated phosphorus solubilization have been conducted under controlled laboratory or greenhouse conditions, often using simplified systems and elevated concentrations of organic acids. However, these conditions do not adequately represent the complexity of natural soil environments, where interactions among soil minerals, microorganisms and plant roots are highly dynamic.

Field-scale validation is therefore limited and the actual contribution of organic acids to phosphorus mobilization under real agricultural conditions remains insufficiently quantified. Long-term field studies are needed to evaluate the persistence, spatial variability and cumulative effects of organic acids on phosphorus availability across different soil types and cropping systems (Hinsinger *et al.*, 2015; Menezes-Blackburn *et al.*, 2018) ^[24, 39].

14.2 Need for Quantitative Understanding

A major limitation in current research is the lack of quantitative assessment of organic acid-mediated processes. While the mechanisms of acidification, chelation and ligand exchange are well established, their relative contributions under field conditions are not clearly defined.

Future research should focus on:

- Quantifying the rates of organic acid production and turnover
- Determining threshold concentrations required for effective P solubilization
- Evaluating the contribution of different organic acids to overall phosphorus mobilization

Advanced analytical techniques, such as isotopic tracing and spectroscopy, can provide deeper insights into the kinetics and pathways of phosphorus transformation in the rhizosphere (Fink *et al.*, 2016) ^[11].

14.3 Rhizosphere Modeling and Process Integration

The rhizosphere is a highly complex microenvironment where multiple biological, chemical and physical processes interact simultaneously. Despite these advances, there is still a lack of robust models that integrate organic acid dynamics with phosphorus cycling at the root-soil interface.

Future efforts should aim to develop:

- Mechanistic models incorporating root exudation, microbial activity and soil chemistry
- Spatial and temporal simulations of organic acid diffusion and reaction kinetics
- Predictive frameworks for phosphorus availability under varying environmental conditions

Such models will be essential for scaling up rhizosphere processes from micro-scale interactions to field-level nutrient management (Hinsinger *et al.*, 2009; Schnepf *et al.*, 2012) ^[23, 57].

14.4 Influence of Climate Change

Climate change is expected to significantly alter soil processes, including organic acid dynamics and phosphorus availability. Changes in temperature, precipitation patterns and soil moisture regimes will directly affect microbial activity, root exudation and organic matter decomposition.

- Increased temperatures may enhance microbial activity and organic acid production but also accelerate their degradation
- Altered rainfall patterns may influence leaching and transport of organic acids
- Drought conditions may reduce root exudation and microbial processes

However, the combined effects of these factors on organic acid-mediated phosphorus solubilization remain poorly understood. Future research should integrate climate variables into studies

of rhizosphere processes to predict how phosphorus dynamics will respond under changing environmental conditions (Sardans and Peñuelas, 2012) [55].

14.5 Future Perspectives for Sustainable Nutrient Management

To fully harness the potential of organic acids in improving phosphorus use efficiency, future research should adopt an integrated approach that combines soil chemistry, plant physiology and microbial ecology. Key priorities include:

- Identification and selection of crop genotypes with enhanced organic acid exudation
- Development of biologically driven nutrient management strategies
- Integration of organic acid dynamics into precision agriculture systems
- Linking rhizosphere processes with sustainable soil fertility management

A deeper understanding of these processes will enable the design of innovative strategies to mobilize soil-bound phosphorus, reduce fertilizer dependency and improve agricultural sustainability.

15. Conclusion

Organic acids play a pivotal role in enhancing phosphorus (P) availability in soils through multiple interacting mechanisms, including proton-induced acidification, metal chelation, ligand exchange, competitive adsorption and mineral dissolution. These processes collectively facilitate the transformation of sparingly soluble phosphorus forms into plant-available pools within the rhizosphere. The efficiency of these mechanisms is strongly influenced by the chemical nature of organic acids and soil physicochemical properties, highlighting the complexity of phosphorus dynamics in soil systems.

The importance of organic acid-mediated phosphorus solubilization lies in its potential to improve phosphorus use efficiency, reduce dependence on chemical fertilizers and support

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