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REVIEW PAPER

A comprehensive review on organic waste compost as an effective phosphorus source for sustainable agriculture

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Abstract

Purpose: The transformation of Organic Waste through composting has become a source of organic matter that, through microbial action, generates molecules conducive to phosphate solubilization and produces fractions of Po and Pi readily available for plants. For this reason, this review focused on analyzing various research studies where Organic Waste is utilized to release available phosphorus and thus improve agricultural production.

Method: One hundred and eighteen articles were analyzed and synthesized from recognized databases, addressing the following topics: Phosphorus in the Earth's crust, phosphorus recovery from Organic Waste, compost, metabolic pathways for phosphorus release in compost, and microbial activity for phosphorus release in compost.

Results: The selection of organic materials and the incorporation of MSP during the composting process favor the availability of P for plants. The compost microbiota associated with phosphorus not only enhances its availability but also may promote plant growth. Various mechanisms exist for P release, such as the enzymes β-1,4-glucosidase and β-D-fructofuranosidase, along with mycorrhizae facilitating P transport, the enzymatic cofactor pyrroloquinoline quinone, and the function of phosphorus genes contributing to its availability, thereby promoting sustainable agricultural practices.

Conclusion: Composts can serve as valuable P sources for plants, wherein their existing microbiota enhances phosphorus availability, facilitating increased phosphorus recycling through symbiotic relationships, microbial interactions, and the action of phosphorus genes, thereby ensuring sustainable agriculture.

Keywords: Enzymatic activity; Organic acids; Organic waste; Phytohormones; Phosphate solubilizers

Introduction

Phosphorus plays a vital role in various physiological functions in plants, such as cell division, root development, and photosynthesis, as it is a component of essential molecules like phospholipids, nucleic acids, and ATP (Ortega 2020). However, despite the assistance of specialized microorganisms in releasing phosphorus from compounds, it remains relatively scarce in the soil for plants (Atoloye 2021).

Phosphorus (P) is the eleventh most abundant element in the Earth's crust (Corbridge 2013), with a gross abundance ranging from 0.10% to 0.12% (w/w) (Fuller 1972; Corbridge 2013). Therefore, total mineral phosphorus concentrations in soil range from 35 to 5300 mg P/Kg, with an average of approximately 800 mgP/Kg to 1400 mgP/kg (Bowen 1979; Azam et al. 2019; Walton et al. 2023). Mineral phosphorus in soil originates from igneous and sedimentary rocks, which are initially insoluble and must be solubilized for plant assimilation (Contrato 2018). This input has been excessive over the years through highly soluble phosphates, and the unused remnants accumulate in the soil, either through multivalent metal chelation or clay and organic matter absorption, requiring application in each crop cycle. High concentrations of phosphate can be found bound to other elements such as Ca, F, or Cl, forming apatite and fluorapatite, ($Ca_5(PO_4)_3F$), chlorapatite ($Ca_5(PO_4)_3Cl$), and hydroxyapatite ($Ca_5(PO_4)_3OH$) (Espinel 2020). Other mineral sources of P include lazulite ((Mg-Fe), $Al_2(PO_4)_2(OH)_2$), strengite ($FePO_4{\cdot}2H_2O$), vauxite ($FeAl_2(PO_4)_2(OH)_2{\cdot}6H_2O$), vivianite ($Fe_3(PO_4)_2{\cdot}8H_2O$), and variscite ($AlPO_4{\cdot}2H_2O$) (Veith and Sposito 1977).

Approximately 30% to 65% of total soil phosphorus exists in organic forms, with the remainder in inorganic forms. Organic forms consist of dead plant/animal residues and soil microorganisms, which are crucial for converting them into plant-usable forms (Tapia-Torres and Garcia-Oliva 2013). However, soil microorganisms may hinder phosphorus absorption through mineralization processes (Kwesi-Asomaning 2020; Singh et al. 2015).

Phosphate rocks, essential for phosphorus compounds and fertilizers, are globally transported at a rate of approximately 30 million tons annually. Morocco, with 85% of its reserves, extracts phosphorus from alkaline intrusive igneous rocks like apatite (Contrato 2018; Azam et al. 2019). Despite finite resources, with about 100 years of reserves left, concerns arise about potential hoarding by major producers and its impact on global food security (Escamilla 2015). Apatite extraction may introduce high levels of heavy metals and radioactive elements, posing risks to biomass and disrupting carbon and nitrogen cycles (Basílio et al. 2022).

Recycling organic materials, such as sewage sludge, Organic Waste, invasive weeds, and agro-industrial residues, offers an alternative phosphorus source (Grigatti et al. 2017; Oliveira 2019; Kauser and Khwairakpam 2022; Hernández-Lara et al. 2021; Zuhair et al. 2022). Studies show that composted organic materials provide superior soil-available phosphorus compared to chemical fertilizers (Adnan et al. 2017). Targeted recycling of Organic Waste and sludge is crucial for reintroducing nutrients into the soil, enhancing biofertilizer production, increasing agricultural output, and addressing public health, environmental protection, and climate change concerns (Galvis 2016; Hernández-Berriel et al. 2016; Vergara and Tchobanoglous 2012).

This review stems from the research question: What molecules present in organic matter wastes have the potential to solubilize phosphates and how can they be managed through composting and its relationship to agricultural production sustainability? For this reason, the primary objective of this work is to identify molecules present in organic matter that possess properties for phosphate solubilization and to explore the composting process of Organic Waste aiming to leverage the phosphorus (P) release capacity as an essential element for plant growth.

In a world where phosphorus availability is crucial for agricultural production, understanding how these molecules can influence phosphate solubilization could be key to improving the efficiency and sustainability of fertilization systems. In this way, it could not only contribute to optimizing the use of natural resources but also to reducing the reliance on synthetic fertilizers and their potential environmental impacts.

Method

One hundred and eighteen articles were obtained from our search, which was conducted following the methodology proposed by Ferenhof and Fernandes (2016). We used Scopus, Science Direct, Web of Science, PubMed, Scielo, Google Scholar, ResearchGate, and Dialnet databases and considered articles published from 1972 to 2023. The search focused on the following keywords or topics: Phosphorus in the Earth's crust, phosphorus recovery from Organic Waste, compost, metabolic pathways for phosphorus release in compost, and microbial activity for phosphorus release in compost.

The need for new sources of Phosphorus in agriculture

Applying P to crops in their assimilable forms leads to better crop yields (Moreno and Moral 2007). However, excessive application through synthetic fertilizers can have adverse effects on its availability since elements such as aluminum (Al) and iron (Fe) in acidic soils or calcium (Ca) in basic soils can sequester P, resulting in significant P loss (Chen et al. 2022). Excessive application also increases P loss through leaching and migration from agricultural soils, leading to eutrophication and subsequent anoxia in marine ecosystems. Therefore, P is prevented from re-circulating, affecting its potential to absorb CO_2 (Fernández-Marcos 2011; Iida and Shock 2011; Richardson et al. 2023). Furthermore, higher prices for phosphate fertilizers due to rising demand and input costs raise production expenses for farmers (Moharana et al. 2020). The above-mentioned reasons have encouraged us to find new P sources and the optimization to its application to optimize its plant uptake.

Phosphorus recovery from organic waste and sewage sludge

An increase in human activity has resulted in a greater variety of waste compositions, with approximately 46% of solid waste being organic, primarily from food preparation (Hoang et al. 2022), where improper management of this Organic Waste can lead to potential contamination (World Bank 2018). Organic Waste (OW) and urban and agro-industrial sewage sludge not only contain abundant organic matter (>40%) but also serve as significant nutrient sources. Sustainable management can valorize these waste materials as nutrients for soil and plants. The OW category includes the organic fraction of municipal solid waste, wood chip waste, agricultural waste, garden waste, food waste, and animal manure, with variations depending on their origin (Table 1).

The phosphorus content of the reviewed OW ranges from 0.05% to 1.78%, indicating relatively low phosphorus values (Moharana 2020; Wei et al. 2018a). In contrast, sewage sludge exhibits higher total phosphorus values (1.53% to 1.78%) (Grigatti et al. 2017) (Table 1). This higher content is likely attributed to soap residues containing phosphorus (Djandja et al. 2022) and residues from food such as legumes, vegetables, cereals, tubers, fruits, and bone waste in the form of organophosphonates (Wei et al. 2018a; Tapia-Torres and García-Oliva 2013). Apart from phosphorus, both OW and sewage sludge contain other essential nutrients for plant growth, including nitrogen, ranging from 0.21% to 3.90%. These nutrients originate from protein-rich materials, amino acids, some B-complex vitamins, and Phytohormones found in fruits, vegetables, and forage. These materials act as food for decomposer microorganisms, thereby stimulating the proliferation of free-living nitrogen-fixing microorganisms. Some of these microorganisms, such as *Aeromonas salmonicida*, *Pausterella pneumotropica*, *Burkholderia tropica*, and *Bacillus sp.*, possess dual functions as they not only fix nitrogen but also solubilize phosphate (Bolívar-Anillo et al. 2016; Corrales et al. 2014; Pérez-Cordero et al. 2014). However, lower nitrogen values can increase the C/N ratio, limiting microbial activity in Organic Waste management (Santamaria and Ferrera 2002).

Another essential nutrient for plant growth is potassium, which plays a role in root cell growth, improving plant nutrient uptake. Potassium content ranges from 0.95% to 2.32% (Moharana et al. 2020; Pedrosa et al. 2013; Pascual et al. 1999), although data on potassium do not usually appear in the reviewed studies. Kitchen waste shows high levels of K, probably caused by banana peels, which are known for their high potassium content. This Organic Waste (OW) and sewage sludge show pH values ranging from 4.83 to 10.2, and they are predominantly basic. Regarding electrical conductivity (EC), they show values below 2, indicating little presence of salts in the raw material, except for MSW (4.90), possibly due to carbonate, sulfate, chloride, or nitrate content (Babana et al., 2013).

Table 1. Chemical characterization of organic waste and sewage sludge.

Origin	Residues	pH	EC (dS/m)	OM %	TOC %	C/N	N %	P %	K %	References
India	OFMSW	7.27	2.06	85.43	40.29	15.20	2.65	ND	ND	(Awasthi et al. 2015)
	WSW	6.54	0.85	94.15	45.18	86.88	0.52			
	AW	7.21	0.86	95.24	44.36	58.36	0.76			
	YW	7.39	0.74	93.14	40.72	45.75	0.89			

CHD	MSW	ND	ND	58.92	34.18	25.30	1.35	ND	ND	(Rana et al. 2018)
MOH				58.27	33.80	22.10	1.53			
PKL				54.99	31.90	27.10	1.10			
(India)										
Mauritius (Africa)	R1	7.40	0.29	81.37	47.20	27.00	1.70	ND	ND	(Soobhany 2018)
	R2	7.30	0.26	65.68	38.10	25.40	1.50			
	R3	7.20	0.19	73.09	42.40	27.20	1.60			
Pombal (Brazil)	CB	ND	ND	43.90	25.46	48.96	0.52	0.15	2.32	(Pedrosa et al. 2013)
	PJ			50.17	29.10	32.69	0.89	0.17	0.20	
	PM			43.96	25.49	20.72	1.23	0.18	0.30	
	SM			39.82	23.09	21.57	1.07	0.52	1.50	
Paipa (Colombia)	MOSW	ND	0.002	61.54	35.70	21.40	1.67	ND	ND	(García-Molano et al. 2021)
Ventaquemada (Colombia)	RC	8.18	ND	77.58	45.00	19.90	2.26	ND	ND	(Bohórquez-Sandoval et al. 2020)
United Kingdom	MSW	6.10	4.90	38.70	ND	1.37	1.64	0.45	0.95	(Pascual et al. 1999)
Italy	AL	10.20	2.00	117.40	68.10	31.80	2.14	1.53	ND	(Grigatti et al. 2017)
	SS	7.90	1.00	47.70	27.70	6.90	3.90	1.78		
	GW	6.80	0.93	43.40	25.20	22.50	1.12	0.26		
China	KW1	4.99	ND	98.99	57.42	17.08	3.36	0.86	ND	(Wei et al. 2017)
	S	7.02		74.63	43.29	47.25	0.91	0.09		
	MM	5.40		93.35	54.15	24.59	2.37	0.78		
India	RS	ND	ND	85.85	49.80	94.20	0.53	0.05	1.07	(Moharana et al. 2020)
	WS			90.68	52.60	90.40	0.58	0.06	1.19	
	MS			87.40	50.70	89.30	0.57	0.08	1.33	
	CS			84.13	48.80	64.70	0.75	0.06	1.19	
	TL			95.85	55.60	121.60	0.46	0.05	1.50	
	CD			64.30	37.30	60.20	0.62	0.14	1.11	
Pakistan	SPW	ND	ND	69.80	40.50	28.30	1.46	0.13	ND	(Billah and Bano 2014)
China	KW2	4.83	1.66	72.85	42.26	13.41	3.15	0.46	ND	(Zhan et al. 2021)
	S	5.61	0.09	81.01	46.99	223.70	0.21	0.21		

EC: electrical conductivity**; OM:** Organic matter**; TOC:** total organic carbon**; N:** total nitrogen**; P:** total phosphorus**; K:** total potassium **CHD:** Chandigarh, **MOH:** Mohali, **PKL:** Pankhula, **OFMSW:** Organic fraction of municipal solid waste, **WSW:** Wood chip waste, **AW:** Agricultural waste, **YW:** Yard waste, **MSW:** Municipal solid waste, **R1:** Food waste, **R2:** Paper waste, **R3:** Garden waste, **CB:** Banana peelings, **PJ:** Jurema pruning, **PM:** Marmeleiro pruning, **SM:** Sheep manure, **MOSW:** Municipal organic solid waste, **RC:** Rumen content, **AL:** Agro-industrial sewage sludge, **SS:** Urban sewage sludge, **GW:** Green waste, **KW:** Kitchen waste, **S:** Sawdust, **MM:** Mixed materials, **RS:** Rice straw, **WS:** Wheat straw, **MS:** Mustard stubble, **CS:** Chickpea stubble, **TL:** Tree leaves, **CD:** Livestock manure, **SPW:** Simple poultry waste.

Phosphorus recycling from OW and sewage sludge: Composting

Composting is a microorganism-driven aerobic process that transforms organic materials into stable organic fertilizers (compost). Composts can enhance soil properties, promoting plant growth, mitigate ing emissions (Hafez et al. 2021; Moreno and Moral 2007; Zhang et al. 2018) and suppress crop pathogens, (Hernández-Lara et al. 2021). Also, microorganisms, including bacteria and fungi, facilitate phosphorus solubilization during composting (Beltrán-Pineda 2015), through the production of Organic Acids or enzymes that increase plantabsorbable phosphorus forms (Oliveira et al. 2009). Specifically, microorganisms transform phosphorus by mineralizing organic phosphorus (Po) via phosphatases and producing low molecular weight Organic Acids, primarily by bacteria solubilizing phosphates from inorganic phosphorus (Pi) (Antoun 2012).

Increasing P availability in compost involves biotechnological manipulation of phosphorus-rich materials, such as manures, phosphate rock, sewage sludge, or biochar during composting (Grigatti et al. 2017; Nobile et al. 2022; Zhang et al. 2018). The use of these materials offers advantages, such as valorizing Organic Waste, reducing production costs (Gao et al. 2019), and enhancing phosphorus solubility in the soil solution, reducing P fixation (Adnan et al. 2017). Also, inoculation during composting with phosphate-solubilizing microorganisms (PSM) boosts phosphates in compost, and it is crucial for low molecular weight Organic Acid production and Enzymatic activity linked to phosphorus solubilization-mineralization (Table 2) (Gaind 2014; Moharana et al. 2020; Yadav et al. 2017; Wei et al. 2018a; Zhan et al. 2021).

In addition to composting, vermicomposting (a process carried out by earthworms, principally the red Californian earthworm, (*Eisenia fetida* or *Eisenia andrei*) can also transform organic residues into compost. This process is more efficient for biologically treating pre-processed materials like livestock manure (Ferraz-Ramos et al. 2022) since it promotes the metabolism of easily assimilable molecules, such as simple carbohydrates, peptides, and proteins. It also increases P, Ca, and Mg levels through the mineralization process of the raw materials used.

Composts have regulations to ensure their quality and safety. In the European Union, Regulation (EU) 2019/1009 on solid organic fertilizers establishes the minimum parameter for P at 1-2% per mass of P_2O_5 (EU 2019). In the specific case of Colombia, solid and liquid organic fertilizers must be endorsed by NTC 5167 (ICONTEC 2011), which also requires reporting if the phosphorus concentration exceeds 1%, as this affects application to soil or crops.

The role of compost microbiota in P availability

The availability of phosphorus in both soil and organic residues is guided by phosphorus-solubilizing microorganisms (bacteria (BSP) and fungi (FSP) and Arbuscular Mycorrhizal Fungi (AMF)), which are specifically responsible for solubilizing or mineralizing it (Fig. 1, Table 2). The principal BSPs for this function is *Pseudomonas, Bacillus, Burkholderia, Kleibsella, Agrobacterium, Aeromonas, Rhizobium, Alcaligenes, Achromobacter,* and *Lactobacillus* (Table 2), while the most representative groups of FSP are *Aspergillus, Penicillium, Trichoderma*, and *Paecilomyces* (Table 2). Most of these microorganisms belong to the rhizosphere of plants, but they can also be found in organic matter, which is the main component of organic residues. P solubilization and mineralization are performed by microorganisms through their metabolism, involving the extracellular production of short-chain Organic Acids for inorganic phosphorus or enzymes for organic phosphorus (Fig. 1). Some microorganisms also perform other functions, such as promoting plant growth (Silva et al. 2023). Thus, their presence is valuable for agriculture.

Microorganisms not producing halozone for phosphorus solubilization may employ alternative mechanisms, such as siderophores, which chelate iron atoms from phosphate compounds. These siderophores are present in gram-negative bacteria, fungi, yeasts, and some plants (Aguado-Santacruz et al. 2012). In contrast, Gram-positive bacteria, known for their resilience to adverse conditions, may be more efficient in phosphate solubilization, particularly in withstanding pH changes during composting and in the soil (Corrales et al. 2014).

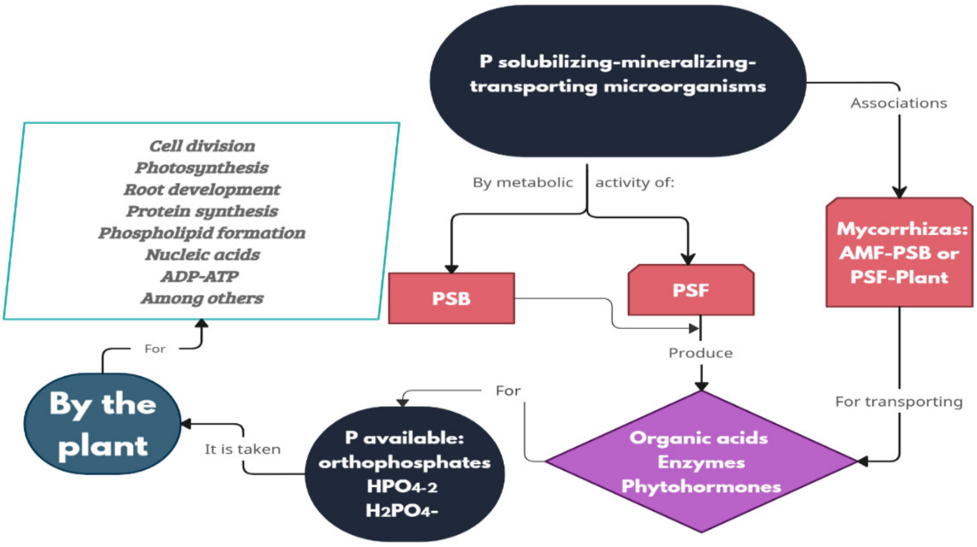

Fig. 1 Mechanisms for obtaining available plant P

PSB: Phosphorus solubilizing bacteria, **PSF:** Phosphorus solubilizing fungi, **AMF:** Arbuscular mycorrhizal fungi.

Arbuscular mycorrhizal fungi (AMF), including *Acaulospora scrobiculata, Glomus deserticola, Glomus intraradices, Glomus versiforme, Acaulospora morrowiae, Acaulospora spinosa, Gigaspora rosea*, *and Rhizophagus intraradices* (Table 2), establish associations in conditions of phosphorus (P) scarcity or immobilization due to the bind with cations like Al, Fe, or Ca. These associations, found in approximately 80% of plant species, involve AMF extending their hyphae into the plant's rhizosphere and penetrating the root cortex, serving various purposes. This includes increased nutrient absorption by the plant, exploration of a larger soil area, enhanced plant biomass, and the provision of organic carbon to AMF. Additionally, AMF contributes to soil stability by producing glomalin and Phytohormones that facilitate P availability to the plant (El Maaloum et al. 2020; Etesami et al. 2021; García-Molano et al. 2022; Perea et al. 2019; Velázquez et al. 2017; Wahid et al. 2020). This mycorrhizal association depends on phosphate-solubilizing fungi (PSF) and, to a lesser extent, phosphate-solubilizing bacteria (PSB) (Fig. 1), which play a crucial role in facilitating interactions between AMF and plant roots. These interactions involve chemical pathways for P solubilization, accomplished through PSF production of low molecular weight Organic Acids or enzymes and hormone secretion. Furthermore, AMF exude fructose, activating phosphatase genes in PSB and promoting organic phosphorus mineralization (El Maaloum et al. 2020; Etesami et al. 2021; Ordoñez et al. 2016). Compost, with organic molecules resembling plant exudates, supports AMF nutrition and growth, facilitating effective P transport to plants. For this reason, when applied to the soil, compost can likely promote mycorrhizal associations, considering its nutritional contributions to AMF (Yang et al. 2018).

Table 2 Phosphorus-solubilizing microorganisms involved in phosphate solubilization, mineralization, and transport

Type	Microorganism	P solubilization mechanisms	References
Bacteria	*Aeromona salmonicida* *Pasteurella pneumotrópica* *Alcaligenes sp.*	Indoleacetic acid (IAA) Alkaline phosphatase enzyme	(Pérez-Cordero et al. 2014; Behera et al. 2017)

Bacteria	*Burkholderia tropica*	Organic acids and phosphatase enzymes. Plant growth promoter (PGP) and siderophore.	(Bolívar-Anillo et al. 2016; Corrales et al. 2014)
Bacteria	*Gluconacetobacter diazotrophicus* *Herbaspirilum seropedicae* *Paenibacillus lautus* *Herbaspirillum sp.* *Azospirillum sp.* *Azotobacter sp*	Phytohormones IAA. PGP	(Restrepo-Franco et al. 2015; Basílio et al. 2022; Pérez-Pazos and Sánchez-López 2017)
Bacteria	*Pseudomonas sp.* *P. aeruginosa* *Rhizobium,* *Burkholderia sp,* *Achromobacter sp* *Agrobacterium,* *Aereobacter* *Flavobacterium* *Yarowia,* *Streptosporangium* *Erwinia herbicola* *Proteus* *Pantoea* *Mycobacterium* *Anthrobacter* *Enterobacter*	PGP Organic acids, phosphatase enzymes, and, in some cases, phytases.	(Babana et al. 2013; Paredes-Mendoza and Espinosa-Victoria 2009; Billah and Bano 2014; Zhang et al. 2021; Estrada-Bonilla et al. 2017; Zhang et al. 2018; Adnan et al. 2017)
Bacteria	*Bacillus sp.; B liqueniformis* *B. amyloliquefaciens; B. megaterium; B. firmus* *Brevibacillus sp*	Organic acids, phosphatase, and phytase enzymes. PGP.	(Estrada-Bonilla et al. 2017; Yadav et.al. 2017; Zhang et al. 2021; Zhan et al. 2021; Adnan et al. 2017)
Bacteria	*Lactobacillus sp* *Herbiconiux sp* *Halopolyspora sp* *Cosenzaea sp* *Aeromicrobium sp* *Cellulosimicrobium sp* *Lentibacillus sp*	Organic acids.	(Estrada-Bonilla et al. 2017; Zhan et al. 2021)
Bacteria	*Klebsella sp.; K. oxytoca* *Micrococcus sp* *Agrobacterium tumefaciens*	Mobilization of organic and inorganic P. Organic acids.	(Zhan et al. 2021; Babana et al. 2013)
Bacteria	Firmicutes Proteobacteria Bacteroidetes	Organic acids.	(Wei et al. 2017)
Bacteria	*Bacillus sp.* *B. megaterium*	Organic acid.	(Castillo-Arteaga et al. 2016; Panhwar et al.

	B. subtilis *B. cereus*		2013; Saeid et al. 2018)
Bacteria	*Pseudomonas sp,* *Pantoea,* *Mycobacterium* *Bacillus,* *Rhizobia,* *Burkholderia,* *Arthrobacter Enterobacter*	Organic acids.	(Adnan et al. 2017)
Bacteria	*Rhizobium tropici* *Acinetobacter sp.* *Paenibacillus kribbensis*	Organic acids.	(Marra et al. 2015)
Haloarchaea	*Haloarcula argentinensis;* *Halobacterium sp.;* *Halococcus sp.;* *Halococcus hamelinensis;* *Haloferax sp., H. alexandrines; H. larsenii; H. volcanii* *Halolamina sp.;* *Halolamina pelagic;* *Halosarcina sp.;* *Halostagnicola kamekura;, Haloterrigena sp.*	Organic acids.	(Yadav et al. 2015)
Fungi	*Aspergillus niger;* *Penicillium pinophilum;* *Talaromyces rotundus;* *Penicillium pimiteouiense;* *Acremonium strictum;*	Organic acids.	(Chuang et al. 2006; Klaic et al. 2017)
Fungi	*Penicillium chrysogenum;* *Aspergillus awamori*	Organic acids. Phosphatase and phytase enzymes.	(Babana et al. 2013)
Fungi	*Aspergillus niger;* *Aspergillus flavus;* *Trichoderma harzianum*	Enzymes: phytase, acid phosphatase + phytase; carboxymethyl cellulase + phosphatase.	(Gaind 2014)
Fungi	*Paecilomyces lilacinus*	Organic acids.	(Hernández-Leal et al. 2011)
Fungi	*Aspergillus niger;* *Penicillium brevicompactum*	Enzymes: phytases. Organic acids.	(Perea et al. 2019)
AMF	*Acaulospora scrobiculata;,* *Glomus sp.;* *G. desertícola;* *G. intraradices;* *G. versiforme*	Enhances the uptake of soluble phosphates in mycorrhizal association.	(El Maaloum et al. 2020)
AMF	*Rhizophagus intraradices*	Enhances the uptake of	(Velázquez et al. 2017)

		soluble phosphates in mycorrhizal association.	
AMF	*Acaulospora morrowiae; Acualospora spinose; Acualospora scrobiculata; Gigaspora rosea; Scutellospora pellucida; Glomus macrocarpum; Funneliformis mosseae; Funnelliformes geosporum; Rhizophagus aggregatus;*	Enhances the uptake of soluble phosphates in mycorrhizal association.	(Perea et al. 2019)

Enzymatic activity (phosphorus mineralization)

Mineralizing organic phosphorus to release orthophosphates occurs when various microbial groups produce extracellular enzymes that synthesize three hydrolytic enzymes: i. phosphonoacetaldehyde hydrolase (phosphonatase), ii. phosphonoacetate hydrolase, iii. phosphonopyruvate hydrolase; iv. C-P lyase breaks the C-P bond, releasing phosphate ion (HPO_4^{-2}) from the organic P source (Kaur 2020; Tapia-Torres and García-Oliva 2013). Pyrophosphatase also hydrolyzes pyrophosphates, which are a group of polyphosphates (Darch et al. 2016). Similarly, non-specific phosphatases dephosphorylate P in phosphorylated proteins, and phytases release P from phytic acid (Kaur 2020). The latter is mainly produced by species of the *Bacillus* and *Enterobacter* genus, which have the advantage of operating within pH ranges of between 3.5 and 7.5 but are more efficient under alkaline pH. Likewise, within the group of phytases, the β-helix phytase should be highlighted for its exceptional phosphate solubilizing activity (Corrales et al. 2014), along with species from the genera *Pseudomonas sp., Burkholderia sp., Alcaligenes sp.,* and *Aspergillus sp.*, which mineralize P by producing phosphatases and phytases (Babana et al. 2013; Behera et al. 2017; Bolívar-Anillo et al. 2016; Cheng and Wan 2022).

Organic acids (phosphate solubilization)

Fungi and bacteria play a crucial role in phosphate solubilization, a process influenced by pH, organic matter interactions, and soil physicochemical characteristics (Babana et al., 2013; Darch et al. 2016). The type of organic acid produced depends on pH, with compost pH being alkaline. Adjusting compost pH to 5.0 enhances organic acid and enzyme efficiency (Darch et al. 2016), however, Marra et al. (2015) propose that organic acid production is pH-independent, and it is mediated by mechanisms like proton exclusion, siderophores, and exopolysaccharide production.

Phosphate-solubilizing microorganisms (PSM), produce organic acids from macromolecules like carbohydrates, lipids, and peptides through a fermentative pathway like glycolysis (Beltrán-Pineda 2015; Paredes et al. 2009). Gluconic acid is produced by *Penicillium rugulosum* from glucose or sucrose, and *Aspergillus niger* produces citric acid through sucrose fermentation (Pérez-Navarro et al. 2016). Gluconic acid releases phosphorus from Ca-P bonding, while oxalic acid releases P from Fe-P and Al-P, acting as chelating agents for these cations (Beltrán-Pineda 2015). Microorganisms like *Pseudomonas sp.* and *Penicillium sp.* produce citric acid, the most efficient organic acid in phosphate solubilization (Babana et al. 2013). Bacteria of the *Bacillus* genus use different pathways, including tricarboxylic acids, to synthesize malic acid or direct glucose oxidation to produce 2-ketogluconic acid (Table 2) (Corrales et al. 2014). Also, certain bacteria, which produce the enzymatic cofactor pyrroloquinoline quinone (PQQ), are known to contribute to the synthesis of organic acids such as gluconic acid, (Sarr et al. 2020; Vera-Cardoso et al. 2017). Fungi present in compost, despite their smaller population, exhibit higher efficiency in P solubilization, attributed to their production of a larger quantity of organic acids compared to bacteria (Babana et al. 2013). On the other hand, the direct action of phosphorus genes on the solubilization of minerals containing it is well established, involving genes such as gcd, ppx, and ppa for Pi, and genes like phoA, phNW, phoD, phnP, phnl, phnG, and phnJ for Po (Xu et al. 2023).

Phytohormones

Phosphate solubilization can also be attributed to phytohormone secretion by various microorganisms from the genera *Pseudomonas, Bacillus, Azotobacter,* and *Azospirillum.* These groups are of interest for phosphate solubilization and also have characteristics such as fixing nitrogen, producing phytohormone, and promoting plant growth (Licea-Herrera et al. 2020). The main Phytohormones studied for phosphorus (P) solubilization include auxins, which promote lateral root production for nutrient absorption while inhibiting primary root growth; ethylene, involved in forming adventitious roots under P deficiency and linked to acid phosphatase regulation (Basílio et al. 2022); and strigolactones, inducing morphological, physiological, and biochemical changes in plants. Strigolactones contribute to increased root biomass, aiding in soil P scavenging through symbiosis with fungi in mycorrhizal formations. Strigolactones may also acidify the environment by releasing protons from root exudates, working in conjunction with phytase and acid phosphatase. However, excess P in plants can negatively impact strigolactone synthesis, reducing dissolved organic carbon exudation (Santoro et al. 2021). Although research on the role of Phytohormones in P solubilization in compost is in its early stages, it highlights another mechanism benefiting organic residues and sludge, not only as a nutrient source for the soil but also as a source of microorganisms, fostering synergistic relationships between microorganisms and plants.

Phosphorus fractions in composts from organic waste and sludge

Phosphorus forms in organic wastes and sludge composts

Phosphorus in compost can be present in different forms: i. labile, corresponding to orthophosphates that are easily assimilated by plants; ii. moderately available phosphorus, which is bound to metals such as Fe, Al, and Ca and can be solubilized through organic and inorganic acids, along with organic phosphorus as phosphate esters that can be mineralized by enzymes to convert it into labile phosphorus; and iii. occluded phosphorus, which is present in molecules that are challenging to solubilize and mineralize (Takahashi and Dahlgren 2016; Tinoco-Varela and Bayuelo-Jiménez 2021; Velásquez et al. 2017). The phosphorus absorbed by plants is mineralized organic phosphorus, which originates from phosphate esters where P is bound to oxygen in its maximum oxidation state (+5), making it highly susceptible to mineralization. There are also phosphonates, where phosphorus is directly bound to carbon, forming bonds that require more energy to break, operating with an oxidation state of +3 (Tapia-Torres and García-Oliva 2013).

Quantification methods of Phosphorous forms

Various methodologies for extracting plant-available P have been developed, among which the most relevant are Colwell (1963), Bray I and II (1945), Mehlich (1984), and Olsen-P (1954); the latter being the most widely used analytical method (Milham et al. 2013). Moharana et al. (2020) indicate that this method is commonly used due to its response to different substrates, making it a good indicator of plant-available P; In some cases, another indicator of availability is citric acid-soluble P at 2% for acidic media (CASP); it is also important to determine the percentage of P solubilization. In response to this, the European Commission proposed the SMT (Standards, Measurements, and Testing) method, which analyzes total phosphorus (TP), inorganic phosphorus (P_i), organic phosphorus (P_o), non-apatite phosphorus (NAP), and apatite phosphorus (AP), aiming for uniformity in fractionation methods (Ruban et al. 2001; García 2014; Velasco 2021).

Phosphorus availability in organic waste composts

The content and availability of phosphorus in composts can increase during the composting process, as indicated by Cheng and Wan (2022, 2023). For instance, compost made from sorghum straw and pig manure exhibited an increase from an initial phosphorus content of 0.5 g/kg to 1.34 g/kg after composting (Table 3). The phosphorus content in composts is influenced by the raw materials used, suggesting that combining various materials can enhance the macronutrient values (Table 3). This results in increased phosphorus content and promotes microorganisms involved in solubilization or mineralization, facilitating the gradual release of phosphorus and preventing losses through leaching or chelation (Vicentin et al. 2021).

Ortega-Torres (2022) demonstrated the production of enzymes like phytases, acid phosphatases, alkaline phosphatases, and neutral phosphatases by inoculating *Pseudomonas aeruginosa* into cattle manure compost. This led to the release of orthophosphate ions, highlighting the synthesis of various enzymes with mineralizing functions. Wan et al. (2020) showed that alkaline phosphatase activity was intense toward the end of composting, potentially favoring increased available phosphorus from organic waste. However, other Enzymatic activities, such as β-1,4-glucosidase, β-D-fructofuranosidase, β-1,4-N-acetylglucosaminidase, and sulfatase, may also influence phosphorus availability, although this relationship has not been extensively studied. Wei et al. (2018a, b) found that formic acid exhibited the most solubilization activity for various forms of phosphorus, including TP, Po, Pi, Olsen-P, PAC (phosphorus soluble in citric acid), and microbial biomass phosphorus (MBP). Oxalic acid acted on TP, Po, Pi, and MBP, while citric acid influenced Po and MBP. These activities occurred during the cooling phase of composting, suggesting that the Organic acids, available phosphorus, and phosphate-solubilizing microorganisms reached the soil, enhancing plant activity.

The total phosphorus content in composts varies depending on the source material, ranging from 2 to 9 g/kg for composts derived from organic waste, sludge, and agro-industrial wastes, to 14 to 17 g/kg for composts produced from manures or animal wastes (Table 3). Post-composting, phosphorus tends to accumulate, with substrate influencing microbial community establishment, particularly in animal manure composts, where phosphorus levels can reach 34 kg/ton (Williams, 2013). However, the majority of available phosphorus comes from organic matter, with content varying based on phosphorus form, carbon, and nitrogen levels (Hernández-Leal et al. 2011). Understanding the native microbiota of composted materials is essential for enhancing process efficiency (Gaind, 2014). Wei et al. (2016) identified key phylogenetic groups involved in phosphorus transformation, such as *Firmicutes, Proteobacteria,* and *Bacteroidetes*, which contribute to the formation of slow-release phosphorus sources for plants. Families like *Pseudomonadaceae, Enterobacteriaceae,* and

Bacillaceae are capable of solubilizing phosphorus in soils and are commonly found in composts and plant rhizospheres. Greater raw material diversity corresponds to increased microbial diversity and enzyme production. When compost is applied to the soil, it promotes mineralization processes of organic phosphorus in the soil's organic matter, laying the foundation for developing techniques to isolate microorganisms synthesizing phosphatases for use as biofertilizers.

The total phosphorus content or availability in composts inoculated with phosphate-solubilizing microorganisms (PSMs) varies based on the raw material type and specific PSMs used. Billah and Bano (2014) observed superior outcomes with the phosphate-solubilizing bacterium *Pseudomonas sp.*, compared to *Proteus sp.* and the control without inoculation, resulting in increased plant height and grain production. Biochar + oil palm bunch compost applied to maize crops fosters populations of phosphate-solubilizing fungi like *Aspergillus sp.* and *Neosartorya sp.*, enhancing microorganism adaptability and promoting maize growth through increased phosphorus absorption. This medium increased phosphorus absorption in maize plants by 100-200%, promoting their growth by producing various compounds. Chen and Wan (2023) highlighted the challenges of decomposing residues with high lecithin levels and demonstrated the mineralization of organic phosphorus (Po) by the WWJ-22 strain of *Pseudomonas sp.,* leading to increased phosphorus availability. Yadav et al. (2017) demonstrated that compost from various sources, including agricultural wastes and manure, with added phosphate rock (PR) and inoculated heat-resistant phosphate-solubilizing bacteria (*Brevibacillus* and *Bacillus*) in wheat cultivation, resulted in elevated total phosphorus levels, shoot and root length, and plant biomass. They emphasized compost as a conditioning medium for phosphate-solubilizing bacteria (PSB), essential for slowly solubilizing phosphorus for plant growth. Babana et al. (2013) compared the solubilization of Tilemsi phosphate rock using bacteria (*Pseudomonas sp.* and *Vibrio splendidus*) and fungi (*Penicillium chrysogenum thom* and *Agrobacterium tumefaciens*) isolated from wheat rhizospheres. Bacteria showed a higher solubility index, but fungi had more elevated solubilized phosphorus (Sarr et al. 2020). The latter demonstrated that heat-resistant phosphate-solubilizing fungi, by the end of composting, had a stronger correlation with labile phosphorus (labile-P) and total phosphorus (TP) than bacteria, along with a higher correlation with alkaline phosphatase activity.

Table 3. Total P and bioavailable P values in different types of compost and vermicompost

Composts	**Total phosphorus (TP) (g/kg)**	**Bioavailable phosphorus (PAV) (g/kg)**	**Reference**
Urban solid organic waste	1.99	ND	(García-Molano et al. 2021)

Wastewater sludge	6.00	2.51	(Grigatti et al. 2017)
Rice straw	8.50	0.90	(Moharana et al. 2020)
Wheat straw	7.80	0.80	
Mustard stubble	6.10	0.75	
Chickpea stubble	6.50	0.70	
Tree branches	6.30	0.62	
Poultry litter without inoculation	230.00	9.60	(Billah and Bano 2014)
Poultry litter with *Pseudomonas sp.*	410.00	17.20	
Poultry litter with *Proteus sp.*	300.00	12.40	
Pig manure	21.95	6.08	(Wei et al. 2015)
Chicken manure	29.99	8.64	
Municipal solid waste	6.76	1.17	
Kitchen waste	3.36	0.78	
Green waste	4.62	1.86	
Rice straw with pig manure	1.34	ND	(Chen and Wan 2023)
Municipal solid waste	3.00	ND	(Ahmadi et al. 2020)
Organic waste	2.10	ND	(Sandoval Duarte et al. 2020)
Organic fraction of urban solid waste	5.40	ND	(Saldarriaga et al. 2018)
Agro-industrial waste	3.20 -8.90	ND	(Hernández-Lara et al. 2021)
Kitchen waste	4.58	0.59	(Zhan et al. 2021)
Ruminal content	15.10	ND	(Bohórquez-Sandoval et al. 2020)
Grape pomace waste:		ND	(Gómez-Brandón et al. 2021)
Almariño variety	0.75		
Mencía variety	1.41		
Mixture of weed waste, manure, and sawdust	12.87	ND	(Kauser and Khwairakpam 2022)
Agro-industrial poultry waste	16.90	ND	(Niedzialkoski et al. 2021)
Vineyard waste	2.00	ND	(Blaya et al. 2013)
Inoculated residual municipal solid waste with PSB	10-18	4.20-8.10	(Wei et al. 2017)
Rice straw and PR	24.20	1.15	(Moharana et al. 2020)
Wheat straw and PR	22.70	1.08	
Mustard stubble and PR	21.00	1.08	
Chickpea stubble and PR	21.60	1.08	
Tree branches and PR	20.90	0.95	
Kitchen waste with PR 5%	20.63	0.29	(Zhan et al. 2021)
PR 10%	31.16	0.74	
PR 15%	40.64	0.45	

Mixture of manures: Cattle, horse, and poultry, adding PR in three concentrations:			(Páez et al. 2022)
Compost with 5% PR	145.00	1.60	
Compost with 10% PR	151.00	1.65	
Compost with 15% PR	215.00	1.70	
Vineyard waste:			
With *Trichoderma harzianum* inoculation	1.50	ND	(Blaya et al. 2013)
Plant and animal waste with *Azospirillum brasilense* inoculation	ND	12.00	(Hafez et al. 2021)
Rice straw + cattle manure	ND	0.62	(Gaind 2014)
Rice straw + farmyard manure	ND	0.74	
Rice straw + poultry manure	ND	1.48	
Rice straw + cattle manure + PSF	7.12	0.85	
Rice straw + farmyard manure + PSF	6.70	0.85	
Rice straw + poultry manure + PSF	9.98	1.56	

PR: Phosphate rock; **PSF:** Phosphate-solubilizing fungi; **PSB:** Phosphate-solubilizing bacteria.

Gaind (2014) observed the concentration of mineralized phosphorus (Po), as measured by Olsen-P, doubling the phosphorus compared to the control treatment in different types of composts (rice straw with poultry manure, rice straw with cattle manure, and rice straw with farmyard manure) inoculated with a consortium of fungi (*Aspergillus niger*, *Aspergillus flavus*, and *Trichoderma harzianum)*. In another study, Hafez et al. (2021) inoculated the bacterium *Azospirillum brasilense* into organic ecological waste compost, resulting in a notable increase in labile phosphorus, highlighting the role of indoleacetic acid (IAA) metabolic pathways in facilitating phosphorus solubilization and enhancing crop production (Table 3).

Additionally, vermicomposting of organic waste contributes phosphorus (P) as an organic fertilizer, facilitated by the mineralization of organic phosphorus within the earthworm's digestive tract and the production of enzymes like phosphatases and phytases. Studies by Bohórquez-Sandoval et al. (2020) and Gómez-Brandón et al. (2021) demonstrated increased total phosphorus (TP) content in vermicomposts derived from different organic materials. Combining composting with vermicomposting has also been explored, revealing promising phosphorus levels in the mix (Kauser and Khwairakpam 2022; Niedzialkoski et al. 2021; Zuhair et al. 2022).

Related to the P absorbed by plants attending to its form, Moreno and Moral (2007) showed that only 20% to 40% of the total phosphorus (P) content is plant-available. This fraction represents labile phosphorus, which constitutes part of the bioavailable phosphorus fractions for plants. The dynamics in soils and, consequently, in crops depend on these contributions. Similarly, phosphorus levels play a crucial role in establishing the microbiota since phosphorus is present in cellular organelles or forms a part of ATP, the primary molecule for cellular energy acquisition. Consequently, plants can also mineralize phosphorus for their metabolic functions (Moreno and Moral 2007).

Yang et al. (2018) found that cattle manure and maize stalk compost applied to soybean cultivation increased the density of arbuscular mycorrhizal fungi (AMF) spores and hyphae. This enhancement favored the flowering and maturation phases of the crop, regardless of the quantity of compost added. These findings suggest that the fungal spores belong to the native soil population of the *Glomeraceae* family. They highlighted that root colonization is influenced by the soybean crop's demand for substantial amounts of phosphorus (P) for atmospheric nitrogen fixation. Furthermore, the hyphae promote a slow and sustained release of labile P for the plant.

Conclusion

The need to find alternative sources of P to maintain sustainable agriculture has turned organic waste composts and sewage sludge into a nutrient source to reduce the use of inorganic sources. Depending on the raw materials used, and also due to the incorporation of phosphorus-solubilizing microorganisms (PSM), their contents can increase as these microorganisms are involved in their solubilization. There are different mechanisms of P solubilization, such as Organic acids, phosphatases, symbiotic relationships, microbial interactions, and the action of phosphorus-related genes, which increase its slow release, reducing the use of highly soluble sources.

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