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Microbial phosphate solubilization mechanisms in p solubilizing in andisol - A review

Abstract. Phosphate (P) nutrient plays a significant role in plant growth and yield. P is an essential element that plays an important role in photosynthesis and root development. Phosphate nutrient availability is deficient in some soil types due to retention, such as in Andisol soil types. High phosphate retention in Andisol soil types causes P nutrients to be unavailable to plants and can reduce crop yields. The availability of P in Andisol soils can be done, among others, by applying phosphate solubilizing microbes. Phosphate solubilizing microorganisms are soil microorganisms consisting of bacteria and fungi that can mineralize organic P, dissolve inorganic P minerals, and store large amounts of P to make it available to plants. This literature review aims to determine the mechanism of phosphate-solubilizing microbes in P dissolution in Andisol soil. The methods used in this systematic review are collecting data through the internet and utilizing recognized sources such as Science Direct, Research Gate, Google Scholar, and Web of Science. Content analysis was performed on the collected data, and the results were organized into thematic categories. Furthermore, the findings are presented descriptively with the help of tables to facilitate understanding. Since phosphate-solubilizing microorganisms can dissolve P in the soil through chemical and biological mechanisms, it can be concluded that phosphate-solubilizing microorganisms also have an important role in the soil P cycle. The implications of this literature review are to understand the retention of P nutrients in Andisols and how the dissolution mechanism works, as well as the use of microbes as a solution to increase phosphate dissolution so that it is available to plants.

Keywords: Andisol · Bacteria · Enzyme · Fungi · Organic acid

Submitted: 20 January 2024, Accepted: 4 August 2024, Published: 14 August 2024
DOI: https://doi.org/10.24198/kultivasi.v23i2.52749

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Marpaung AE, Sabrina T, Rauf A, Susilowati DN, Siregar LAM. 2024. Microbial phosphate solubilization mechanisms in P solubilizing in Andisol - A review. Jurnal Kultivasi, 23(2): 227-238.

ISSN: 1412-4718, eISSN: 2581-138x

Introduction

Phosphate (P) is important in plant growth and development and is responsible for its metabolic activities and functions (Ahmad et al., 2018). Phosphate is also the second important element after N, and it plays an important role in photosynthesis and root development (Billah et al., 2019). Conversely, a P deficit can result in weak, sluggish, and stunted plant growth, as Sharma et al. (2013) noted. According to the statement, farmers frequently employ inorganic phosphate fertilizers to get the highest possible crop yield (Sharma et al., 2015). Although there is a lot of element P in the soil, most of it is insoluble, limiting its availability. Just 0.1% of the total P in plants is available in the soil (Zhu et al., 2018). Precipitation with cations in the soil, immobilization, adsorption, and interconversion to organic forms cause fixation reactions that result in low availability of P despite the large reserves in the soil (Kishore et al., 2015).

Crop productivity can be raised with proper fertilization. of applying chemical, organic, and biological fertilizers can increase the availability of nutrients in the soil. Phosphate-solubilizing microorganisms are one type of microorganism found in biofertilizers. As Tian et al. (2021) stated, using microbes as phosphate solvents is one of the best steps for agricultural development. The production of organic acids and acid phosphatase enzymes, which are involved in mineralizing organic phosphate in the soil, constitute the primary mechanism of phosphate mineral dissolution (Setiawati and Pranoto, 2015). In general, practically all tropical soil types have the issue of poor P availability; Andisol soil is one example. The most reactive allophane clay minerals are found in andisols (Farmer et al., 1991). Because of their high P retention and subsequent P adsorption, which renders P inaccessible to plants, andisols have lower P availability (Marpaung et al., 2021; Sukarman and Dariah, 2014).

This literature review aims to determine the mechanism of phosphate-solubilizing microbes in P dissolution in Andisol. This literature review hypothesizes that phosphate-solubilizing microbes can dissolve P through organic and inorganic P dissolution in the Andisol.

Methodology

This study describes a systematic literature review conducted between November 2023 and March 2024 in Medan, Indonesia. The study used a contextual analysis approach to collect data from various secondary sources. The internet served as the primary platform for data collection, utilizing reliable sources such as Science Direct, Research Gate, Google Scholar, and Web of Science. The collected data underwent content analysis, and the results were organized into thematic categories. The findings were then presented descriptively, with the help of tables to enhance understanding.

Result and Discussion

Andisol. Acidic parent materials (liparites) with a high aluminum (Al) content are the source of andisols. Amorphous minerals like allophane dominate the volcanic ash material that forms andisols. Indonesian andisol soils range in pH from 3.4 to 6.7, with an average of 5.4. However, the most common pH range is between 4.5 and 5.5, with the pH range between 5.5 and 6.5 being the second most common. Andisol soils often have low bulk densities, high water contents at 15 bars, moderate to low plant water availability, and high water contents. One feature of soils with amorphous minerals (>85%), such as allophane minerals by 97.8%, is high P retention (Sukarman and Dariah, 2014).

Andisols exhibit a range of chemical properties that indicate the parent material's impact and degree of weathering. Among the chemical characteristics of Andisol soils, soil organic matter, aluminum, iron, and active silica are the most important components controlling chemical reactions. Al-humus complex, imogolite, ferihydrite, and allophane are the primary forms of active Al and Fe. Alophanes possess a huge specific surface area and several active functional groups, making them the most reactive clay minerals. Alofan can fix substantial amounts of phosphate because it is amphoteric, has a high variable charge, and has cation and anion exchange capacities of 20 to 50 cmol (+) kg-1 and 5 to 30 cmol (+) kg-1, respectively (Tan, 1991). Andisols also feature distinct strata connected to the intermittent deposition of volcanic material, mottling, a dark topsoil color, and a highly loose/weak and granular structure (Anda dan Dahlgren 2020).

According to (Zhu et al., 2018), Andisol soils are so effective at binding phosphate nutrients because they are bound mainly by non-crystalline clay minerals such as ferihydrite, imogolite, and allophane. P can be retained by allophane up to 97.8%. Consequently, even if there is a lot of P in the soil overall, there is less P available to plants—roughly 0.1% of the total P. According to Uchida et al. (2022), the ferrihydrite system does not precipitate Al-phosphate, but the allophane and allophane-ferrihydrite mixed systems precipitate Al-phosphate. Compared with the iron affinity in soil, volcanic ash soil shows a phosphate affinity for Al between 61 - 92%.

Phosphate in Andisol. The chemical characteristics of the parent material and the growth of the plants it supports greatly influence the biological activity of the soil, which serves as both a medium for plants and an ecological niche with ongoing biological activity. The quantity of phosphorus in the environment available for biosynthesis is influenced by both its total amount and its solubility, which is established by some chemical reactions and biological interactions in the soil. Three broad categories can be used to classify the various forms of soil P: soil solution P, insoluble organic P, and insoluble inorganic P (Weil and Brady 2019).

One of the important nutrients for plants is phosphate (P) for optimal growth and yield. Phosphate available in the soil can be absorbed directly by plants. Organic phosphate is available in soil in the form of inositol phosphate, especially hesaphosphate, namely in the form of orthophosphate ions $H_2PO_4^-$ and HPO_4^{-2}, and inorganic phosphate includes Al-P, Fe-P, and Ca-P (Billah et al., 2019; Zhu et al., 2018). Cylandic Andisols appear to play an important role in the adsorption of crystalline iron species. On the other hand, Gonzalez-Rodriguez and Fernandez-Marcos (2018) found that the richness of cylandic Andisol in non-crystalline iron and aluminum causes its high absorption. The high content of allophane, active aluminum, and free iron in other volcanic soils is proportional to their phosphate uptake and irreversibility. The dissolved form of P is easily fixed and removed from the soil solution through adsorption reactions.. This chemical reaction mainly occurs on the surface of amorphous aluminum (Al) and iron (Fe) hydroxides in highly weathered volcanic ash soils and tropical soils (Osorno et al., 2018).

$$\underset{\text{(in silicate crystals)}}{(Al)} + H_2PO_4^- + 2H_2O \rightarrow 2H^+ + \underset{\text{(not dissolved)}}{Al(OH)\,2H_2PO_4}$$

$$\underset{\text{(in silicate crystals)}}{(Fe)} + H_2PO_4^- + 2H_2O \rightarrow 2H^+ + \underset{\text{(not dissolved)}}{Fe(OH)\,2H_2PO_4}$$

Calcium phosphate is found in alkaline soils, whereas aluminum and iron phosphate are the primary forms of phosphorus in acidic soils (Kumar and Shastri, 2017). According to Zhu et al., (2018), phosphorus immobilization in soil is significantly influenced by the pH of the soil. One of the key elements that increase phosphorus mobilization in paddy soil through iron(III)-reducing bacteria is soluble organic carbon, which provides microorganisms with energy (Khan *et al*., 2019).

Phosphate-Solubilizing Microbes. Phosphate-solubilizing microorganisms (PSMs) are bioinoculants that show potential as agrochemical alternatives (Table 1). They use a variety of techniques to convert insoluble phosphorus into soluble forms. As a result, they can reduce the amount of phosphate fertilizer applied to agricultural land (Hussain et al., 2019). Phosphate-dissolving microorganisms create chemicals, including organic acids, mineral acids, and siderophores to dissolve insoluble phosphate minerals and release ions such as PO_4^{-3}, HPO_4^{-2}, and $H_2PO_4^-$, (Marpaung and Susilowati, 2021; Sembiring et al., 2016).

Bacteria belonging to the genera *Pseudomonas*, *Enterobacter*, and *Bacillus* (Biswas et al., 2018), *Rhizobium*, *Arthrobacter*, dan *Burkholderia*, and *Rahnella aquatilis* HX2 (Liu et al. 2019; Zhang et al. 2022), and fungi *Penicillium brevicompactum* and *Aspergillus niger* (Perea Rojas et al. 2019), is a proper phosphate solubilizing microbe. *Bacillus amyloliquefaciens*, *Bacillus pseudomycoides*, and *Bacillus cereus* are phosphate-solubilizing bacteria found in the potato rhizosphere, according to a study conducted by Marpaung and Susilowati (2021) on Andisol soil. Susilowati et al. (2020) identified *Penicillium singorense* and *Clonostachys* sp. as phosphate solubilizers from acid-sulfate soils in South Kalimantan, Indonesia. Other *Bacillus* species that are phosphate-solubilizing bacteria include *B. subtilis*, *B. amyloliquefaciens*, *B. pumilus* (Borriss, 2014), and *B. mycoides* (Setiawati and Pranoto, 2015). These species have the potential

ISSN: 1412-4718, eISSN: 2581-138x

to dissolve phosphate qualitatively (Ulfiyati and Zulaika, 2015), which can improve soil nitrogen and phosphate availability. *Bacillus amyloliquefaciens* is another bacterium that boosts N and P absorption in corn (Vinci et al., 2018). Ulfiyati and Zulaika (2015) use of *Bacillus* species to qualitatively dissolve phosphate supports this. Phosphate-solubilizing bacteria up to 0.1-0.5% of the entire microbial population, whereas fungi, which are greater phosphate solubilizers, make up about 1-50% (Kalayu, 2019).

A sustainable and eco-friendly method of treating P deficit in agricultural soils is using phosphate-solubilizing microorganisms (Sharma et al., 2013; Kalayu, 2019). The production of phosphatase enzymes and organic acids is the basic mechanism by which phosphate minerals in the soil dissolve (Setiawati and Pranoto, 2015). By secreting organic acids such as citric, lactic, glycolic, 2-ketogluconic, oxalic, glyconic, acetic, malic, fumaric, succinic, tartaric, malonic, glutaric, propionic, butyric, glyoxalic, and adipic acids, phosphate-solubilizing microorganisms increase the availability of phosphorus (Kalayu, 2019).

Mechanism of Phosphate Solubilization by Microbes. Mechanism of phosphate dissolution by phosphate-solubilizing microbes in the soil consists of inorganic phosphate dissolution and organic phosphate dissolution. Dissolution by phosphate-solubilizing microbes will produce phosphate available to plants and utilized for growth (Figure 1).

Solubilization of Inorganic Phosphate. According to Alori *et al*., (2017), the primary processes by which phosphate-solubilizing bacteria solubilize P include synthesizing organic acids, the manufacture of phytase and acid phosphatase, and reducing pH. Phosphorus can be made available to plants by organic acids like citric acid, oxalic acid, and succinic acid; enzymes like phosphatase and phytase; and ion chelators such siderophores (Tomer *et al*., 2016).

Organic Acid Production. Low molecular weight organic acids are released, the widely acknowledged method by which phosphate-solubilizing microorganisms can solubilize phosphate (Table 2). Pollutant detoxification, heavy metal bioavailability, and even microbial activity under soil conditions are all significantly impacted by low molecular weight organic acids (Onireti et al., 2017). Billah et al. (2019) showed that phosphate-solubilizing microbes release gluconic acid, oxalic acid, tartaric acid, and lactic acid, which help lower soil pH. This creates practical conditions under which the monovalent (available) occurs. Lowering the pH near plant roots by releasing citric acid has several immediate benefits. First, it moves the pH to a region where HPO-4 ions dominate and facilitate absorption. Additionally, low pH naturally increases phosphate release (Barrow et al., 2018). These mechanisms include the chelation of cations bound to phosphate, pH lowering, complexation with metal ions bound to phosphate, and challenging P for adsorption sites *(*Kishore et al., 2015). However, different phosphate-solubilizing bacteria produce different dominating organic acids (Panhwar et al., 2014). Higher concentrations of organic acids are necessary for phosphate-solubilizing bacteria to mobilize significant amounts of insoluble phosphate and convert it to soluble form by direct oxidation of phosphate on the cytoplasmic membrane (Wei et al., 2017; Chen et al., 2014).

According to Herzberg and Elimelech (2008), in Andisol, the relative surface charge of cells will bind to the charge of soil clay minerals, limiting the adsorption of clay minerals to phosphate. Furthermore, phosphate-solubilizing bacteria organic acid anions can obstruct soil sorption sites (Borggaard et al., 2005).

The findings demonstrated that the phosphate solubilizer *Pseudomonas* sp. AZ15 could generate soluble phosphorus up to 109.4 μg mL^{-1}, boosting yields in chickpeas, including dry matter accumulation, grain yield, nodule count, and nodule dry weight. According to Zaheer et al. (2019), this strain produces the organic acids oxalic acid, gluconic acid, acetic acid, lactic acid, and citric acid. By creating organic acids such as ascorbic acid, citric acid, malic acid, gluconic acid, and phytic acid in soybean, *Trichoderma* was also able to solubilize phosphorus (AMS 34.39, AMS 31.15, and AMS 1.43) and boost plant growth by 41.4% in comparison to control plants (Bononi et al., 2020). According to Schneider et al. (2019), oxidative respiration or fermentation in the presence of organic carbon sources (sucrose and glucose) are the mechanisms underlying organic acid formation.

Table 1. Types of phosphate-solubilizing microbes in soil.

Phosphate-Solubilizing Microbes	Reference
B. subtilis, B. amiliquefaciens, B. pumilus	(Borriss 2015)
B. mycoides	(Setiawati and Pranoto, 2015)
Klebsiella variicola, Ochrobactrum pseudogrignonense	(Nacoon et al., 2020)
Staphylococcus haemolyticus, *Staphylococcus cohnii*	(Hii et al., 2020)
Pseudomonas putida, *Leclercia adecarboxylata*	(Teng et al., 2019)
B. cereus, B. amyloliquefaciens, and *B. Pseudomycoides*	(Marpaung and Susilowati, 2021)
Rahnella aquatilis HX2, *Burkholderia cenocepacia*	(Liu et al., 2019; Zhang et al., 2019)
Pseudomonas fulva, *Enterobacter* sp	(Munir et al., 2019)
Bacillus megaterium, *Bacillus licheniformis, Rhizobium* sp	(Biswas et al., 2018; Li et al., 2018)
Arthrobacter defluvii, Pseudomonas frederiksbergensis, Rhodanobacter sp., Bacillus cepacia, Vibrio paradoxus	(Zheng et al., 2019)
Acinetobacter, *Aeromonas*, *Arthrobacter*, *Bacillus*, *Citrobacter*, *Enterobacter*, *Halomonas*, *Microbacterium*, *Ochrobactrum*, *Pantoea*, *Providencia*, *Pseudomonas*, *Sinomonas*, dan *Streptomyces*	(Susilowati et al., 2015; Chen et al., 2006)
Rhizobium, Pseudomonas and Bacillus	(Sharma et al., 2013)
Penicillum sp. PK112, *Trichoderma harzianum* OMG08	(Mercl et al., 2020)
Aspergillus aculeatus P93, *Penicillium daleae, Aspergillus versicolor*	(Adhikari and Pandey 2019)
Acremonium, *Hymenella*, *Neosartorya*	(Ichriani et al., 2018)
Penicillium brevicompactum, *Aspergillus niger*	(Perea Rojas et al., 2019)
Penicillium oxalicum	(Li et al., 2016)
Cephalosporium, *Arthrobotrys*, *Aspergillus*, *Achrothcium*, *Cladosporium*, *Alternaria*, *Chaetomium*, *Phoma*, *Micromonospora*, *Rhizoctonia*, *Penicillium*, *Fusarium*, *Mortierella*	(Fatima et al., 2022)

Table 2. Organic acid-producing phosphate-solubilizing microbes.

Phosphate-Solubilizing Microbes	Organic acid	Reference
Pantoea agglomerans NCTC 9381, *Pantoea vagans* LMG 24199, *Pseudomonas azotoformans* NBRC 12693, *Enterobacter ludwigii* EN-119, *Serratia quinivorans* 4364	Citrate, fumarate, acetate, succinate, gluconate, oxalate	(Rfaki et al., 2020)
Bacillus cereus, Bacillus subtilis, Paenibacillus sp.	Oxalate, malate, formate, acetate, tartarate, gluconate	(Chawngthu et al., 2020)
Pseudomonas, Burkholderia, Klebsiella, Achromobacter, Sphingobacterium	Gluconate, oxalate, lactate, acetate, malate, tartarate	(Nacoon et al., 2020)
Trichoderma sp.	Citrate, lactate, malate, fumarate, ascorbate, isocytic, phytate	(Bononi et al., 2020)
Leclercia adecarboxylata B3	Citrate, formate, gluconate, malonate, acetate, succinate	(Teng et al., 2019)
Bacillus megaterium, Bacillus subtilis, Bacillus licheniformis	Citrate, acetate, propionate, lactate	(do Carmo et al., 2019)
Penicillium oxalicum, Aspergillus niger	Citrate, oxalate, formate, tartarate, malate, acetate	(Li et al., 2016)
Pseudomonas, Burkholderia, Klebsiella, Achromobacter, Sphingobacterium	Citrate, gluconate, oxalate	(Mendes et al., 2014)

Jurnal Kultivasi Vol. 23 (2) August 2024
ISSN: 1412-4718, eISSN: 2581-138x

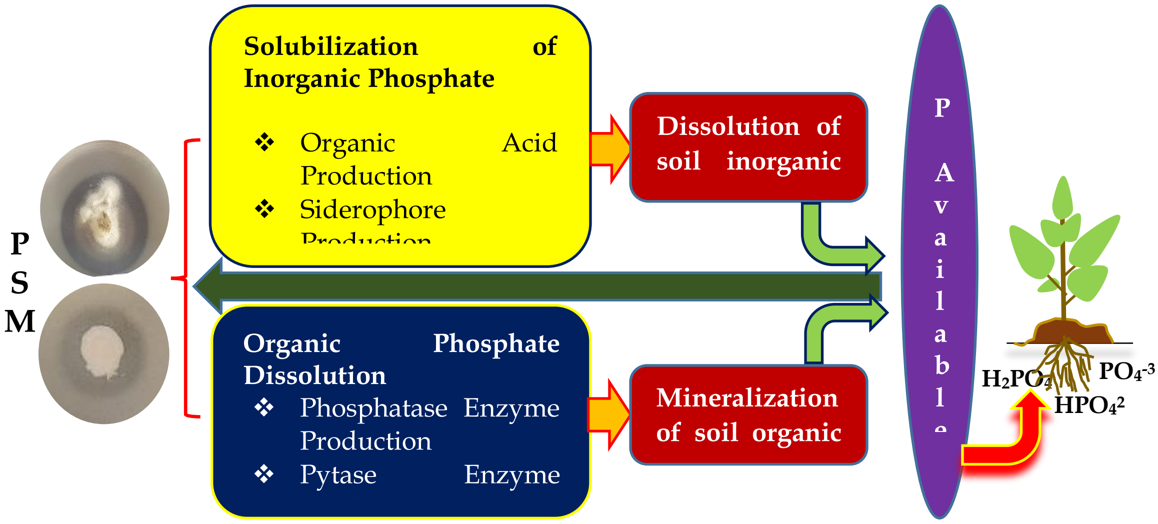

Figure 2. Schematic of phosphate solubilization mechanism by phosphate-solubilizing microbes.

Siderophore Production. Siderophores are a chemically diverse group of secondary metabolites with a high affinity for iron (Gu et al., 2020). Recently, it has been shown that they can be used in various fields, such as bioremediation of heavy metals, stopping phytopathogens, and promoting plant growth. Some microbes that produce siderophores from phosphate solvents are *Beauveria brongniartii* (Toscano-Verduzco et al., 2020), *Bacillus* sp. STJP (Prakash and Arora, 2019), *Pseuomonas* sp. P34 (Liu et al., 2019), *Streptomyces laurentii* (Kour et al., 2020), *Bacillus megaterium*, *Bacillus subtilis, Rhizobium radiobacter*, and *Pantoea allii* are a few phosphate-solubilizing microbes that produce siderophores and can help organisms survive in harsh environments (Ferreira et al., 2019).

Organic Phosphate Dissolution. In soil, 20–30% of the total phosphorus comprises organic phosphate. Enzymes use the process of mineralization to dissolve organic phosphate (Kumar and Shastri, 2017). Bi et al. (2018) found that soil microbes can activate the soil P cycle by promoting extracellular hydrolysis of Po compounds and facilitating the turnover of bioavailable phosphate sources such as H_2O-Pi, $NaHCO_3$-Pi, and NaOH-Pi. This biogeochemical process is controlled by the activity of phosphatase enzymes in the soil and phosphate-solubilizing microbes (Sun et al., 2020). Streptomyces spp. also generate phospholipase, phytase, phosphodiesterase, and phosphoesterase (Kalayu, 2019). Phosphatases catalyze the dephosphorylation of organic molecules' phosphoester or phosphoanhydride bonds. The findings indicate that bacteria secrete basic and acidic phosphatases (Sharma et al., 2013). *Zea mays* L. roots and stems had percentages of phosphorus content that were increased by 2.35 and 1.76 times, respectively, by *Bacillus licheniformis* MTCC 2312 (Singh and Banik, 2019). When the phosphate-solubilizing fungus *Talaromyces helices* L7B and the arbuscular mycorrhizal fungus *Rhizophagus* were co-injected into soil, the results showed an irregular increase in soil alkaline phosphatase activity (459.38 EU) relative to uninoculated soil (47.86 EU) and a 50% increase in soil soluble phosphorus (Della et al., 2020).

The primary source of inositol and phosphorus reserves in seeds and pollen is compound phytate, or rich organic phosphorus in the soil, which is catalyzed by the enzyme phytase to remove phosphorus (Sharma et al., 2013). Cereal crops injected with phytase-producing bacteria absorbed more phosphate without fertilizers (Martínez et al., 2015). Phytase (133 IU) and phosphatase (170 IU) at their maximal levels were produced by the phosphate-solubilizing fungus *Aspergillus niger* in 48 hours of solid-state fermentation, together with soluble phosphorus up to 835 ppm. According to Ben Zineb et al., (2020), strains of *Pseudomonas corrugata* SP77 and *Serratia* *liquefaciens* LR88 were found to be able to produce phytase, and they both demonstrated phytase activity up to 23.02 and 24.84 U mL-1, respectively. They also showed increased phosphorus solubilization efficiency of 714.96 and 306.74 µg mL-1, respectively.

Conclusion

In Andisol, the relative surface charge of cells will bind to the charge of soil clay minerals, limiting the adsorption of clay minerals to phosphate. Phosphate solubilizing microbes can dissolve insoluble phosphate minerals in Andisol through organic and inorganic phosphate dissolution mechanisms by producing organic acids and siderophores, biosynthesis of acid phosphatase and phytase, and lowering the pH so that they can release ions such as HPO_4^{-2}, and $H_2PO_4^-$ which can be absorbed by plants. Phosphate solubilizing bacteria organic acid anions can obstruct soil sorption sites. Using phosphate-dissolving microbes as a phosphate solvent is one of the best environmentally friendly alternatives for sustainable agriculture.

Reference

Adhikari P, Pandey A. 2019. Phosphate solubilization potential of endophytic fungi isolated from *Taxus wallichiana* Zucc. roots. Rhizosphere, *9*: 2-9. https://doi.org/10.1016/j.rhisph.2018.11.002

Ahmad M, Ahmad M, El-Naggar AH, Usman AR, Abduljabbar A, Vithanage M, Elfaki J, Abdulelah AF, Al-Wabel MI. 2018. Aging effects of organic and inorganic fertilizers on phosphorus fractionation in a calcareous sandy loam soil. Pedosphere, 28: 873–883.

Ahmed E, Holmström SJ. 2014. Siderophores in environmental research: roles and applications. Microbial biotechnology, *7*(3): 196-208. https://doi.org/10.1111/1751-7915.12117

Alori ET, Glick BR, Babalola OO. 2017. Microbial phosphorus solubilization and its potential for use in sustainable agriculture. Frontiers in microbiology, 8: 971. https://doi.org/10.3389/fmicb.2017.00971

Anda M, Dahlgren RA. 2020. Mineralogical and surface charge characteristics of Andosols experiencing long-term, land-use change in West Java, Indonesia. Soil Sci. Plant Nutrition, 66(5):702-713.

Barrow NJ, Debnath A, Sen A. 2018. Mechanisms by which citric acid increases phosphate availability. Plant and soil, 423: 193-204

Ben Zineb A, Trabelsi D, Ayachi I, Barhoumi F, Aroca R, Mhamdi R. 2020. Inoculation with elite strains of phosphate-solubilizing bacteria enhances the effectiveness of fertilization with rock phosphates. Geomicrobiology journal, 37(1): 22-30. https://doi.org/10.1080/01490451.2019.1658826

Bi QF, Zheng BX, Lin XY, Li KJ, Liu XP, Hao XL, ... Zhu Y G. 2018. The microbial cycling of phosphorus on long-term fertilized soil: Insights from phosphate oxygen isotope ratios. Chemical Geology, 483:56-64.

Billah M, Khan M, Bano A, Hassan TU, Munir A, Gurmani AR. 2019. Phosphorus and phosphate solubilizing bacteria: Keys for sustainable agriculture. Geomicrobiology Journal, 36(10): 904-916.

Biswas JK, Banerjee A, Rai M, Naidu R, Biswas B, Vithanage M, ... Meers E. 2018. Potential application of selected metal resistant phosphate solubilizing bacteria isolated from the gut of earthworm (*Metaphire posthuma*) in plant growth promotion. Geoderma, *330*: 117-124. https://doi.org/10.1016/j.geoderma.2018.05.034

Borggaard OK, Raben-Lange B, Gimsing AL, Strobel BW. 2005. Influence of humic substances on phosphate adsorption by aluminium and iron oxides. Geoderma *127*(3-4): 270-279. https://doi.org/10.1016/j.geoderma.2004.12.011

Bononi L, Chiaramonte JB, Pansa CC, Moitinho MA, Melo IS. 2020. Phosphorus-solubilizing *Trichoderma* spp. from Amazon soils improve soybean plant growth. Sci Rep. 10: 1–13. https://doi.org/10.1038/s41598-020-59793-8

Borriss R. 2014. *Bacillus*, a plant-beneficial bacterium. In *Principles of plant-microbe interactions: microbes for sustainable agriculture*. (pp. 379-391). Cham: Springer

Jurnal Kultivasi Vol. 23 (2) August 2024
ISSN: 1412-4718, eISSN: 2581-138x

international publishing. https://doi.org/10.1007/978-3-319-08575-3_40

Borriss R. 2015. *Bacillus*, a Plant Beneficial Bacterium. In Lugtenberg, B (Ed). Principles of Plant-Microbe Interactions. Microbes for Sustainable Agriculture. Springer Publishing, Switzerland: 379- 391. https://doi.org/10.1007/978-3-319-08574-6

Cao L, Gao Y, Yu J, Niu S, Zeng J, Yao Q, ... Zhu Y. 2021. *Streptomyces hygroscopicus* OsiSh-2-induced mitigation of Fe deficiency in rice plants. Plant Physiology and Biochemistry, 158: 275-283.

Chawngthu L, Hnamte R, Lalfakzuala R. 2020. Isolation and characterization of rhizospheric phosphate solubilizing bacteria from wetland paddy field of Mizoram, India. Geomicrobiology Journal, *37*(4): 366-375. https://doi.org/10.1080/01490451.2019.1709108

Chen Y, Fan JB, Du L, Xu H, Zhang QH, He YQ. 2014. The application of phosphate solubilizing endophyte Pantoea dispersa triggers the microbial community in red acidic soil. Appl. Soil Ecol. 84: 235-244. https://doi.org/10.1016/j.apsoil.2014.05.014

Chitraselvi RPE, Kalidass S, Rajiv K. 2015. Efficiency of rhizosphere bacteria in production of indole acetic acid, siderophore and phosphate solubilization. International Journal of ChemTech Research, *7*(6): 2557-2564. http://sphinxsai.com/2015/ch_vol7_no6...

Della Mónica, IF, Godeas AM, Scervino JM. 2020. In vivo modulation of arbuscular mycorrhizal symbiosis and soil quality by fungal P solubilizers. *Microbial ecology*, *79*(1), 21-29. https://doi.org/10.1007/s00248-019-01396-6

Din M, Nelofer R, Salman M, Khan FH, Khan A, Ahmad M, Khan M. 2019. Production of nitrogen fixing Azotobacter (SR-4) and phosphorus solubilizing *Aspergillus niger* and their evaluation on *Lagenaria siceraria* and *Abelmoschus esculentus*. Biotechnology Reports, *22*, e00323. https://doi.org/10.1016/j.btre.2019.e00323

do Carmo TS, Moreira FS, Cabral BV, Dantas RC, de Resende MM, Cardoso VL, Ribeiro EJ. 2019. Phosphorus recovery from phosphate rocks using phosphate-solubilizing bacteria. Geomicrobiology Journal, *36*(3): 195-203. https://doi.org/10.1080/01490451.2018.1534901

Fatima F, Ahmad MM, Verma SR, Pathak N. 2022. Relevance of phosphate solubilizing microbes in sustainable crop production: a review. International Journal of Environmental Science and Technology, *19*(9): 9283-9296. https://doi.org/10.3389/fmicb.2017.00971

Farmer VC, McHardy WJ, Palmieri F, Violante A, Violante P. 1991. Synthetic allophanes formed in calcareous environments: Nature, conditions of formation, and transformations. Soil Science Society of America Journal, *55*(4): 1162-1166. https://doi.org/10.2136/sssaj1991.03615995005500040044x

Ferreira CM, Vilas-Boas Â, Sousa CA, Soares HM, Soares EV. 2019. Comparison of five bacterial strains producing siderophores with ability to chelate iron under alkaline conditions. AMB Express, *9*(1): 78. https://doi.org/10.1186/s13568-019-0796-3

Gonzalez-Rodriguez S, Fernandez-Marcos ML. 2018. Phosphate sorption and desorption by two contrasting volcanic soils of equatorial Africa. *PeerJ. 6*, e5820.

Gu S, Wei Z, Shao Z, Friman VP, Cao K, Yang T, ... Jousset A. 2020. Competition for iron drives phytopathogen control by natural rhizosphere microbiomes. Nature Microbiology, 5(8): 1002-1010.

Hassan TU, Bano A. 2015. Role of carrier based biofertilizer in reclamation of saline soil. Archives Agron. Soil. Sci. 61(12): 1719-1731. https://doi/abs/10.1080/03650340.2015.1036045

Herzberg M, Elimelech M. 2008. Physiology and genetic traits of reverse osmosis membrane biofilms: a case study with *Pseudomonas aeruginosa*. The ISME Journal, *2*(2): 180-194. https://doi.org/10.1038/ismej.2007.108

Hii YS, San Chan Y, Lau SW, Michael D. 2020. Isolation and characterization of phosphate solubilizing microorganisms from peat. Biocatal Agric Biotechnol, 26, 101463. https://doi.org/10.1016/j.bcab.2020.101643

Hussain A, Adnan M, Hajira SI, Fahad S, Saeed M, Mian IA, ... Andaleeb S. 2019. Combining phosphorus (P) with phosphate solubilizing bacteria (PSB) improved wheat yield and P uptake in alkaline soil. Pure and Applied Biology, 8(2): 1809-1817. https://doi.org/10.19045/bspab.2019.80124

Ichriani GI, Nuraini Y, Handayanto 2018. Formulation of biochar compost and phosphate solubilizing fungi from oil palm empty fruit bunch to improve growth of maize in an ultisol of Central Kalimantan. *J Ecol Eng*. 19, 45–55. https://doi.org/10.12911/22998993/92891

Ingle KP, Padole DA. 2017. Phosphate solubilizing microbes: An overview. International Journal of Current Microbiology and Applied Sciences, *6*(1): 844-852. http://dx.doi.org/10.20546/ijcmas.2017.601.099

Kalayu G. 2019. Phosphate solubilizing microorganisms: Promising approach as biofertilizers. Int J Agron. Article ID. 4917256. https://doi.org/10.1155/2019/4917256

Khan I, Fahad S, Wu L, Zhou W, Xu P, Sun Z, ... Hu R. 2019. Labile organic matter intensifies phosphorous mobilization in paddy soils by microbial iron (III) reduction. Geoderma, 352: 185-196. https://doi.org/10.1016/j.geoderma.2019.06.011

Khan A, Gupta A, Singh P, Mishra AK, Ranjan RK, Srivastava A. 2020. Siderophore-assisted cadmium hyperaccumulation in *Bacillus subtilis*. International microbiology, 23: 277-286.

Kim DY, Kadam A, Shinde S, Saratale RG, Patra J, Ghodake G. 2018. Recent developments in nanotechnology transforming the agricultural sector: a transition replete with opportunities. Journal of the Science of Food and Agriculture, 98(3): 849-864. https://doi.org/10.1002/jsfa.8749

Kishore N, Pindi PK, Reddy SR. 2015. *Phosphate-solubilizing microorganisms: a critical review*. In: Bahadur B, Venkat Rajam M, Sahijram L, Krishnamurthy K. (eds) Plant Biology and Biotechnology. Springer, New Delhi, pp 307–333. https://doi.org/10.1007/978-81-322-2286-6_12

Kour D, Rana KL, Kaur T, Sheikh I, Yadav AN, Kumar V, ... Saxena AK. 2020. Microbe-mediated alleviation of drought stress and acquisition of phosphorus in great millet (*Sorghum bicolour* L.) by drought-adaptive and phosphorus-solubilizing microbes. Biocatalysis and Agricultural Biotechnology, *23*, 101501. https://doi.org/10.1016/j.bcab.2020.101501

Kumar R, Shastri B. 2017. Role of phosphate-solubilising microorganisms in sustainable agricultural development. In *Agro-Environmental Sustainability: Volume 1: Managing Crop Health* (pp. 271-303). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-49724-2_13

Li Z, Bai T, Dai L, Wang F, Tao J, Meng S, ... Hu S. 2016. A study of organic acid production in contrasts between two phosphate solubilizing fungi: *Penicillium oxalicum* and *Aspergillus niger*. Scientific reports, *6*(1), 25313. https://doi.org/10.1038/srep25313

Li H, Li Z, Qu J, Tian H, Yang X. 2018. Combined effects of phosphate-solubilizing bacterium XMT-5 (*Rhizobium* sp.) and submerged macrophyte *Ceratophyllum demersum* on phosphorus release in eutrophic lake sediments. Environmental Science and Pollution Research, 25: 18990-19000. https://doi.org/10.1007/s11356-018-2022-2

Liu C, Mou L, Yi J, Wang J, Liu A, Yu J. 2019. The eno gene of *Burkholderia cenocepacia* strain 71-2 is involved in phosphate solubilization. Current Microbiology, 76: 495-502. https://doi.org/10.1007/s00284-019-01642-7

Martinez OA, Crowley DE, Mora ML, Jorquera MA. 2015. Short-term study shows that phytate-mineralizing rhizobacteria inoculation affects the biomass, phosphorus (P) uptake and rhizosphere properties of cereal plants. J Soil Sci Plant Nutr. 15: 153–166. https://doi.org/10.4067/S0718-95162015005000013

Marpaung AE, Hanum H, Sembiring M. 2021. The effect of liquid organic fertilizer and phosphate solubilising bacteria *Bacillus* sp on potato growth (*Solanum tuberosum*) in andisol soil. In IOP Conference Series: Earth and Environmental Science, 807(4): 042079, July. IOP Publishing. https://doi.org/10.1088/1755-1315/807/4/042079

Marpaung AE, Susilowati DN. 2021. Isolation and identification of phosphate solubilising bacteria from potato rhizosphere on andisol. In IOP Conference Series: Earth and Environmental Science, 810(1): 012041, August. IOP Publishing. https://doi.org/10.1088/1755-1315/810/1/012041

Mendes GDO, Zafra DL, Vassilev NB, Silva IR, Ribeiro Jr JI., Costa MD. 2014. Biochar enhances Aspergillus niger rock phosphate solubilization by increasing organic acid production and alleviating fluoride toxicity. Applied and Environmental Microbiology, 80(10): 3081-3085. https://doi.org/10.1128/AEM.00241-14

Mercl F, García-Sánchez M, Kulhánek M, Košnář Z, Száková J, Tlustoš P. 2020. Improved phosphorus fertilisation efficiency of wood ash by fungal strains *Penicillium* sp. PK112 and *Trichoderma harzianum* OMG08 on acidic soil. Applied Soil Ecology, 147, 103360. https://doi.org/10.1016/j.apsoil.2019.09.010

Mitra D, Anđelković S, Panneerselvam P, Senapati A, Vasić T, Ganeshamurthy AN, ... Radha TK. 2020. Phosphate-solubilizing microbes and biocontrol agent for plant nutrition and protection: current perspective. Communications in Soil Science and Plant Analysis, 51(5): 645-657. https://doi.org/10.1080/00103624.2020.1729379

Munir I, Bano A, Faisal M. 2019 Impact of phosphate solubilizing bacteria on wheat (*Triticum aestivum*) in the presence of pesticides. Braz J Biol., 79: 29–37. https://doi.org/10.1590/1519-6984.172213

Nacoon S, Jogloy S, Riddech N, Mongkolthanaruk W, Kuyper TW, Boonlue S. 2020. Interaction between phosphate solubilizing bacteria and arbuscular mycorrhizal fungi on growth promotion and tuber inulin content of *Helianthus tuberosus* L. Scientific reports, 10(1): 4916. https://doi.org/10.1038/s41598-020-61846-x

Ojuederie OB, Babalola OO. 2017. Microbial and plant-assisted bioremediation of heavy metal polluted environments: a review. International journal of environmental research and public health, 14(12): 1504. https://doi.org/10.3390/ijerph14121504

Onireti OO, Lin C, Qin J. 2017. Combined effects of low-molecular-weight organic acids on mobilization of arsenic and lead from multi-contaminated soils. Chemosphere, 170: 161-168. https://doi.org/10.1016/j.chemosphere.2016.12.024

Osorno L, Osorio NW, Habte M. 2018 'Phosphate desorption by a soil fungus in selected Hawaiian soils differing in their mineralogy. Tropical Agriculture, 95(2): 154–166.

Panhwar QA, Naher UA, Jusop S, Othman R, Latif MA, Ismail MR (2014). Biochemical and molecular characterization of potential phosphate-solubilizing bacteria in acid sulfate soils and their beneficial effects on rice growth. PloS one, 9(10): e97241. https://doi.org/10.1371/journal.pone.0116035

Penn CJ, Camberato JJ. 2019. A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. Agriculture, 9(6): 120. https://doi.org/10.3390/agriculture9060120

Perea Rojas YDC, Arias RM, Medel Ortiz R, Trejo Aguilar D, Heredia G, Rodríguez Yon Y. 2019. Effects of native arbuscular mycorrhizal and phosphate-solubilizing fungi on coffee plants. Agroforestry Systems, 93: 961-972. https://doi.org/10.1007/s10457-018-0190-1

Prakash J, Arora NK (2019). Phosphate-solubilizing *Bacillus* sp. Enhances growth, phosphorus uptake and oil yield of *Mentha arvensis* L. 3 Biotech, 9(4): 126. https://doi.org/10.1007/s13205-019-1660-5

Rfaki A, Zennouhi O, Aliyat FZ, Nassiri L, Ibijbijen J. 2020. Isolation, selection and characterization of root-associated rock phosphate solubilizing bacteria in moroccan wheat (*Triticum aestivum* L.). Geomicrobiology Journal, 37(3): 230-241. https://doi.org/10.1080/01490451.2019.1694106

Schneider KD, Thiessen Martens JR, Zvomuya F, Reid DK, Fraser TD, Lynch DH, ... Wilson HF. 2019. Options for improved phosphorus cycling and use in agriculture at the field and regional scales. Journal of Environmental Quality, 48(5): 1247-1264. https://doi.org/10.2134/jeq2019.02.0070

Sembiring M, Elfiati D, Sutarta ES, Sabrina T. 2016. Effect of *Burkholderia cepacia* and SP36 on available phosphate and potato production on Andisol impacted by Mount Sinabung Eruption, North Sumatera, Indonesia. Journal of Applied Horticulture, 18(3): 233-235. DOI:https://doi.org/10.37855/jah.2016.v18i03.41.

Setiawati MR, Pranoto E. 2015. Perbandingan Beberapa Bakteri Pelarut Fosfat Eksogen Pada Tanah Andisol Sebagai Areal Pertanaman Teh Dominan Di Indonesia. Jurnal Penelitian Teh Dan KIna, 18: 159–164.

Sharma SB, Sayyed RZ, Trivedi MH, Gobi TA. 2013. Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. SpringerPlus, 2: 1-14. https://doi.org/10.1186/2193-1801-2-587

Sharma R, Walia A, Chauhan A, Shirkot CK. 2015. Multi-trait plant growth promoting bacteria from tomato rhizosphere and evaluation of their potential as bioinoculants. Applied Biological Research, 17(2): 113-124. Doi: 10.5958/0974-4517.2015.00019.1

Singh P, Banik RM. 2019. Effect of purified alkaline phosphatase from *Bacillus licheniformis* on growth of Zea mays L. Plant Science Today, 6(sp1): 583-589. https://doi.org/10.14719/pst.2019.6.sp1.676

Suárez-Moreno ZR, Vinchira-Villarraga DM, Vergara-Morales DI, Castellanos L, Ramos FA, Guarnaccia C ... Moreno-Sarmiento N. 2019. Plant-growth promotion and biocontrol properties of three Streptomyces spp. isolates to control bacterial rice pathogens. Frontiers in microbiology, 10: 290. https://doi.org/10.3389/fmicb.2019.00290

Sukarman, Dariah A. 2014. *Tanah Andisol di Indonesia Karakteristik, Potensi, Kendala dan Pengelolaan* (Badan Penelitian dan Pengembangan Pertanian, Bogor) pp. 156

Sun F, Song C, Wang M, Lai DY, Tariq A, Zeng F, ... Peng C. 2020. Long-term increase in rainfall decreases soil organic phosphorus decomposition in tropical forests. Soil Biology and Biochemistry, 151, 108056.

Susilowati DN, Sudiana IM, Mubarik NR, Suwanto A. 2015. Species and functional diversity of rhizobacteria of rice plant in the coastal soils of Indonesia. Indones J Agric Sci., 16: 39–51

Susilowati DN, Sofiana I, Atmini KD, Yuniarti E. 2020. Penapisan Kapang Asal Lahan Sulfat Masam Kalimantan Selatan Sebagai Penghasil Enzim Ekstraseluler. Agric, 32(1): 65-82. https://doi.org/10.24246/agric.2020.v32.i1.p65-82

Tan KH. 1991. *Dasar-dasar Kimia Tanah*. Gadjah Mada University Press. Yogyakarta.

Teng Z, Shao W, Zhang K, Huo Y, Li M. 2019. Characterization of phosphate solubilizing bacteria isolated from heavy metal contaminated soils and their potential for lead immobilization. J Environ Manag, 231: 89–197. https://doi.org/10.1016/j.jenvman.2018.10.012

Tian J, Ge F, Zhang D, Deng S, Liu X. 2021. Roles of phosphate solubilizing microorganisms from managing soil phosphorus deficiency to mediating biogeochemical P cycle. Biology, 10(2): 158.

Tomer, S., Suyal, D. C., & Goel, R. (2016). Biofertilizers: a timely approach for sustainable agriculture. In: Choudhary D, Varma A, Tuteja N (eds) Plant-microbe interaction: an approach to sustainable agriculture. Springer, Singapore, pp 375–395. https://doi.org/10.1007/978-981-10-2854-0_17

Toscano-Verduzco FA, Cedeño-Valdivia PA, Chan-Cupul W, Hernandez-Ortega HA, Ruiz-Sanchez E, Galindo-Velasco E, Cruz-Crespo E. 2020. Phosphates solubilization, indol-3-acetic acid and siderophores production by *Beauveria brongniartii* and its effect on growth and fruit quality of *Capsicum chinense*. J Hortic Sci Biotechnol, 95: 235–246. https://doi.org/10.1080/14620316.2019.1662737

Uchida S, Hashimoto Y, Takamoto A, Noguchi K, Klysubun W, Wang SL 2022. Phosphate binding to allophane and ferrihydrite with implications for volcanic ash soils. Soil Science Society of America Journal, 86(6): 1571-1581.

Ulfiyati N, Zulaika E. 2016. Isolat *Bacillus* pelarut fosfat dari kalimas surabaya. Jurnal Sains dan Seni ITS, 4(2). https://doi.org/10.12962/j23373520.v4i2.14049

Vinci G, Cozzolino V, Mazzei P, Monda H, Savy D, Drosos M, Piccolo A. 2018. Effects of

ISSN: 1412-4718, eISSN: 2581-138x

Bacillus amyloliquefaciens and different phosphorus sources on Maize plants as revealed by NMR and GC-MS based metabolomics. Plant and Soil, 429: 437–450. https://doi.org/10.1007/s11104-018-3701-y

Wei Y, Zhao Y, Fan Y, Lu Q, Li M, Wei Q, Zhao Y, Cao Z, Wei Z. 2017. Impact of phosphate-solubilizing bacteria inoculation methods on phosphorus transformation and long-term utilization in composting. Bioresour. Technol., 241: 134-141.

Weil, R. R., & Brady, N. C. (2019). Elements of the nature and properties of soils. Fourth edition. NY, NY, Pearson.

Zaheer A, Malik A, Sher A, Qaisrani MM, Mehmood A, Khan SU, ... Rasool M. 2019. Isolation, characterization, and effect of phosphate-zinc-solubilizing bacterial strains on chickpea (*Cicer arietinum* L.) growth. Saudi journal of biological sciences, 26(5): 1061-1067. https://doi.org/10.1016/j.sjbs.2019.04.004

Zhang L, Fan J, Feng G, Declerck S. 2019. The arbuscular mycorrhizal fungus *Rhizophagus irregularis* MUCL 43194 induces the gene expression of citrate synthase in the tricarboxylic acid cycle of the phosphate-solubilizing bacterium *Rahnella aquatilis* HX2. Mycorrhiza, 29: 69–75. https://doi.org/10.1007/s00572-018-0871-7

Zhang Y, Li TT, Wang LF, Guo JX, Lu KK, Song RF, ... Liu WC. 2022. Abscisic acid facilitates phosphate acquisition through the transcription factor ABA INSENSITIVE5 in Arabidopsis. Plant J., 111: 269–281.

Zheng BX, Ding K, Yang XR, Wadaan MA, Hozzein WN, Peñuelas J, Zhu YG. 2019. Straw biochar increases the abundance of inorganic phosphate solubilizing bacterial community for better rape (*Brassica napus*) growth and phosphate uptake. Science of the total environment, 647: 1113-1120. https://doi.org/10.1016/j.scitotenv.2018.07.454

Zhu J, Li M, Whelan M. 2018. Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: a review. Sci Total Environ, 612: 522–537. https://doi.org/10.1016/j.scitotenv.2017.08.095