**JOURNAL OF DEGRADED AND MINING LANDS MANAGEMENT**
Volume 11, Number 4 (July 2024):6351-6366, doi:10.15243/jdmlm.2024.114.6351
ISSN: 2339-076X (p); 2502-2458 (e), www.jdmlm.ub.ac.id

**Review**

# Performances of phosphate-solubilizing microorganisms on soil chemical properties under different soil characteristics: a meta-analysis

**Taufiq Bachtiar[1*], Akhmad Rasyid Syahputra[2], Ania Citraresmini[1,3], Ratih Nurjayati[1], Hidawati[1], Veny Rachmawati[1], Asep Mulyono[1]**

[1] Research Center for Environmental and Clean Technology, Research Organization for Life Science and Environment, BRIN, Cibinong, Indonesia
[2] Research Center for Radiation Process Technology, Research Organization for Nuclear Technology, BRIN, Serpong, Indonesia
[3] Faculty of Agriculture, Padjadjaran University, Jatinangor, Sumedang, Indonesia

[*]corresponding author: tauf012@brin.go.id

*Article history:*
Received 20 March 2024
Revised 5 May 2024
Accepted 28 May 2024

*Keywords:*
bacteria
chemical characteristics
fungi
meta-analysis
PSM

## Abstract

The addition of phosphate-solubilizing microorganisms (PSM) as biofertilizers can improve the quality of soil properties. A meta-analysis study was conducted to analyze the effect of PSM on soil properties. This meta-analysis has analyzed 20 research articles published between 1990 and 2023, which have reported the influence of PSM on soil properties. The value of effect size (ES) Hedges'*d* of available-P is 3.047 ($p<0.001$), ES of available K is 2.102 ($p<0.001$), ES of soil nitrogen (N) is 1.706 ($p<0.001$), ES of pH is -2.738 ($p<0.001$), ES of soil organic carbon (SOC) is 1.087 ($p=0.004$), ES of $N\text{-}NH_4$ is 0.636 ($p=0.013$), ES of $N\text{-}NO_3$ is 2.643 ($p<0.001$), ES of phosphatase is 5.001 ($p<0.001$), ES of alkaline phosphatase is 22.956 ($p<0.001$), and ES of acid phosphatase is 23.104 ($p<0.001$). The results showed that in terms of phosphate solubility, PSM is more effective on alkaline soils with high SOC content, very high P availability, and a sandy loam texture. PSM is more effective for K solubility on acidic soils, with very high SOC content, high P availability, and a loamy texture. PSM is effective in increasing soil N with acid soil characteristics, low SOC content, moderate available P content, and clay texture. According to this study, the *Penicillium* fungus ranks second in the fungal group in terms of phosphate solubilization capacity after the genus *Azotobacter.* The genus *Peronospora* showed the greatest potential in increasing soil N. In contrast, *Burkholderia* showed the greatest effectiveness in solubilizing K.

**To cite this article:** Bachtiar, T., Syahputra, A.R., Citraresmini, A.C., Nurjayati, R., Hidawati, Rachmawati, V. and Mulyono, A. 2024. Performances of phosphate-solubilizing microorganisms on soil chemical properties under different soil characteristics: a meta-analysis. Journal of Degraded and Mining Lands Management 11(4):6351-6366, doi:10.15243/jdmlm.2024.114.6351.

## Introduction

One of the macronutrients that is important for plant growth and development is phosphate (P). P is involved in many biological processes in plants, including photosynthesis, energy transfer, signal transduction, macromolecular biosynthesis, and respiration. At least, P is a component of ATP, adenosine triphosphate, the main energy currency in plants. It also constitutes nucleic acids and phospholipids, structural components for membranes. Plants without enough P grow slowly, develop weak roots, and have low yields (Khan et al., 2010; Plaxton and Tran, 2011; Kolodiazhnyi, 2021). Applying P to the soil as P chemical fertilizer is not usually successful. The soil characteristics, including soil organic matter content, greatly influence P availability in the soil (Taalab et al., 2019; Barlog et al., 2020).

Organic matter helps to chelate (bind) P, increasing its availability to plants. Furthermore, organic matter might release P during the decomposition process (Gurmu, 2019). In clay-rich soils, phosphorus tends to become bound to clay particles, decreasing plant availability. Leaching can reduce the availability of P to plants in sandy soils (Martins et al., 2018). Soil pH is one of the most important elements affecting P availability. In acidic soils (pH<6), P is bound to iron and aluminum in insoluble forms. In alkaline soils (pH>7.5), P can also be fixed, although it is frequently linked to calcium, rendering it unavailable to plants. Soils with pH ranges between 6 and 7.5 are generally considered optimal for P availability (Penn and Camberato, 2019).

Increasing soil phosphorus with living microorganisms is a more sustainable and useful approach. Biofertilizers are substances that contain living microorganisms. Phosphate-solubilizing microorganisms are bacteria and fungi that break the bound molecule or intractable forms of phosphate in soil and ionize it electrically. The Phosphate-solubilizing bacteria are critical components for plant growth because they make phosphorus more accessible in the soil (Fitriatin et al., 2017; Fitriatin et al., 2021). In dissolving phosphate, there are several mechanisms used by PSM, such as through the production of organic acids, enzymes, and siderophores, which chelate iron and aluminum ions bound to phosphate release ase (Islam et al., 2019; Martyniuk et al., 2019; Perraud et al., 2019). PSM can come from bacterial groups such as *Bacillus*, *Pseudomonas*, and *Rhizobium*, while fungal PSM can come from groups such as *Aspergillus*, *Penicillium*, and *Trichoderma* (Fatima et al., 2022).

Increased crop yields and reduced use of chemical fertilizers due to the application of PSM to soil have been widely reported. However, several studies report that the use of PSM on soil is not significant (Liu et al., 2015; Santana, 2016). The effectiveness of PSM in the soil is sometimes limited in increasing P availability because PSM is stressed in the soil, so it is vulnerable to environmental conditions. In addition, PSM has different characteristics and varying effectiveness. Apart from depending on its ability to dissolve phosphate, it also depends on the type of soil, type of plant, and other environmental factors (Naveed et al., 2015).

Several studies on PSM revolve around in vitro tests to screen the best phosphate-solubilizing bacteria or fungi rapidly. In vitro tests, in most cases, involve the addition of PSM onto a culture medium containing different forms of insoluble phosphates like tricalcium phosphate, iron phosphate, and aluminum phosphate. After some days or hours, the amount of soluble phosphate is obtained, as shown in the following reaction equation (Kumar et al., 2014; Joe et al., 2018). Through in vitro, the ability of PSM to dissolve phosphate can be useful initial information. However, this test does not reflect actual conditions in the soil because the environment is considered the main driver of ecosystems and the distribution of living organisms (Aqeel et al., 2023). Phosphate solubility can be increased by adding an effective amount of PSM to the soil. Topsoil and soil with a high organic matter content tend to support more diverse and abundant microbial populations. Unbalanced fertilization, especially N and P deficiencies, can limit community function (Herre et al., 2022). In addition, appropriate soil pH also plays an important role in determining the abundance of PSM in the soil.

Based on these matters, the researchers aimed to analyze the effect of PSM on soil on P availability in different soil chemical characters (pH, organic C, available P) through meta-analysis methods, which are expected to provide results in the form of a summary of existing data in journals have been published so far. This research helps determine the compatibility between PSM applications and soil chemical characteristics. This research analyzed 98 globally sourced studies from 20 published literature, then synthesized them to examine the direct effect of PSM on soil available P.

In this study, the researchers conducted a meta-analysis to summarize the capacity of PSM in soil with the aims of (1) analyzing and comparing its effect on available P levels on different soil chemical characters to provide a reference for future research and (2) providing valuable suggestions for the agricultural sector by exploiting the trend of various biofertilizer applications in various soil conditions so that they can be applied more effectively.

## Methods

### *Database collection*

Journal articles collected as a database were obtained from Google Scholar, Springer, and Elsevier. Relevant scientific journal articles are identified using the terms "phosphate-solubilizing microorganism", "bacteria", "fungi", "soil", and "available P". Articles are journals that are relevant to keywords published from 2005 to 2020 (Table 1). The authors only cited complete articles where all data was available for statistical analysis. The inclusion criteria for an article used in this study were as follows: (1) the article was published in English; (2) experiments were carried out with the application of microorganisms to the soil as a treatment to see the effect on available P; (3) the chemical soil characteristics of the experiments reported in the article were limited to soil pH, available P, and soil organic C content; and (4) P availability parameters in the article were obtained from the measurement results with no less than three repetitions of the experiment with targets without PSM treatment (control group) and PSM treatment (treatment group). After examining the titles and abstracts of each journal and the articles discussing especially the availability of P in the soil due to the influence of phosphate-solubilizing microorganisms using PRISMA protocol (Haddaway et al., 2022) (Figure 1), a total of 98 paired P available data under PSM addition experiments from 20 journal articles that met the inclusion criteria were obtained (Figure 1), which were then analyzed using the OpenMee software (Wallace et al., 2017). Each entity was coded separately if an article reports more than one pilot study. All experiments in the article must contain phosphate-solubilizing microorganism inoculations carried out directly on the soil; any experiment testing the effectiveness of PSM on a medium other than soil medium was excluded from the study. The concentrations of phosphate-solubilizing microbes in the culture broth in this meta-analysis ranged from 0 to $10^9$ CFU $mL^{-1}$ for bacteria and 0 to $10^5$ spore $mL^{-1}$ for fungi, with experimental periods varying from 15 to 85 days, in addition to soil P available, information including the first author, publication year, site location (country), microorganism genus, crop type, and soil properties before treatment (soil pH, soil organic carbon, available P, and soil texture).

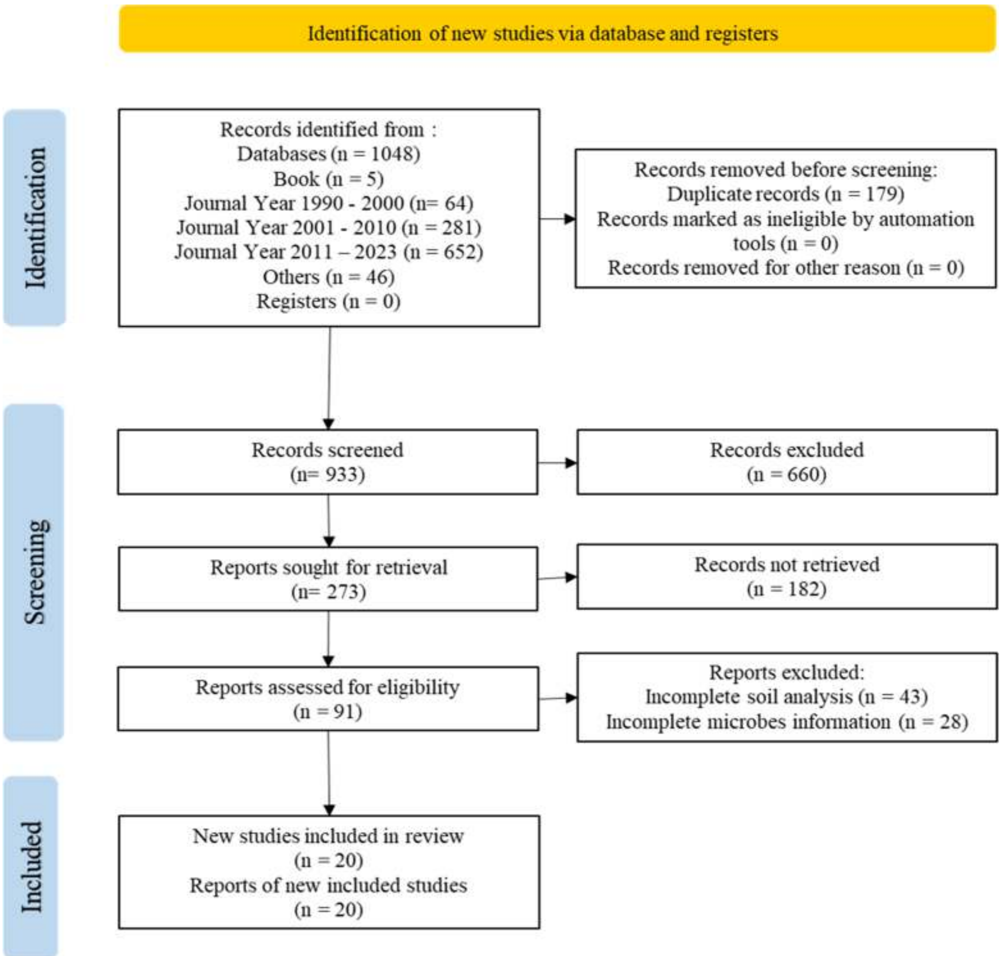


Figure 1. Diagram of literature search based on PRISMA protocols.

***Data preparation***

For the comparison of the effect of PSM on available P, experimental soil was divided into several variable categories: soil pH, soil organic C, soil available P, and soil texture. Experimental sites were grouped according to soil pH ($H_2O$) into very acid (<4.5), acid (4.5-5.5), slightly acid (5.5-6.5), neutral (6.6-7.5), slightly alkaline (7.6-8.5), alkaline (>8.5). Furthermore, experimental sites were separated into five groups based on their soil organic content(%): very low(<1), low(1-2), moderate (2-3), high (3-5), and very high (>5). Then the experimental sites were also divided into five groups based on their P availability (ppm) before inoculation: very low (<4), low (5-7), moderate (8-10), high (11-15), and very high (>15). The experimental sites were also grouped according to soil texture into loam, sandy loam, silt loam, clay, sandy clay, and unknown texture.

The type of crop and microorganism genus was divided into twelve (peanut, barley, paddy, bean, tomato, maize, wheat, chili, chickpea, cowpea, cabbage, and without plant) and fifteen categories (*Acinetobacter, Azospirillum, Azotobacter, Bacillus, Enterobacter, Enterococcus, Erwinia, Lysinibacillus, Paenibacillus, Pantoea, Penicillium, Pseudomonas, Rhizobium, Serratia*, and unknown isolates), respectively.

Table 1. Experiments included in the meta-analysis of the effect of PSM addition on different soil characteristics.

| No | Reference | Soil pH | Crop | Microbes genus | Av-P Status | SOC content |
|---|---|---|---|---|---|---|
| 1 | Canbolat (2006) | Neutral | Barley | *Bacillus* | Moderate | Low |
| 2 | Hariprasad and Niranjana (2009) | Neutral | Tomato | *Bacillus; Pseudomonas; Azotobacter; Enterobacter; Pseudomonas; Serratia;* and unknown strain | Very High | High |
| 3 | Duarah et al. (2011) | Acid | Paddy; Bean | *Erwinia, Pseudomonas* | Moderate | Very Low |
| 4 | Patel et al. (2008) | Alkaline | Chickpea | *Pseudomonas* | Very High; High | Very Low |
| 5 | Singh and Reddy (2011) | Alkaline | Wheat; Maize | *Penicillium* | Very Low | Very Low |
| 6 | Swain et al. (2012) | Neutral | Cowpea | *Bacillus* | Very Low | Very Low |
| 7 | Turan et al. (2012) | Neutral | Wheat | *Bacillus* | Very Low | Low |
| 8 | Wu et al. (2012) | Slightly Acid | | *Bacillus* | Very High | Very High |
| 9 | Xiao et al. (2013) | Neutral | Wheat | *Aspergillus* | Low | Low |
| 10 | Singh et al. (2013) | Slightly Acid | Chickpea | *Enterobacter; Rhizobium* | Very Low | Very Low |
| 11 | Kaur and Reddy (2014) | Alkaline | Maize; Wheat | *Pantoea; Pseudomonas* | Very Low | Very Low |
| 12 | Wang et al. (2014) | Acid | Peanut | *Bacillus* | Low | Very Low |
| 13 | Anzuay et al. (2015) | Neutral | Peanut | *Enterococcus; Bacillus; Acinetobacter; Enterobacter; Pantoea; Serratia* | Low | Low |
| 14 | Kaur and Reddy (2015) | Alkaline | Maize; Wheat | *Pantoea; Pseudomonas* | Very Low | Very Low |
| 15 | Kudoyarova et al. (2017) | Acid | Wheat | *Pseudomonas; Paenibacillus* | Very High | Very High |
| 16 | Rafique et al. (2017) | Alkaline | Maize | *Bacillus; Lysinibacillus* | Very Low | Very Low |
| 17 | Wang et al. (2017) | Alkaline | Cabbage | *Bacillus* | Very Low | Moderate |
| 18 | Linu et al. (2019) | Neutral | Chilli | *Pseudomonas* | Low | Low |
| 19 | Chouyia et al. (2020) | Alkaline | Barley | *Streptomyces* | Very High | Moderate |
| 20 | Xu (2023) | Acid | Pinus | *Pseudomonadota; Burkholderia; Peronospora; Penicillium* | Low | Moderate |

***Meta-analysis***

OpenMEE software features for meta-analyses in ecology and evolutionary biology were used to carry out this research (Wallace et al., 2017). The natural log reaction ratio (R equation) was used as a dimension of the impact induced by the PSM treatment compared to the control. Create response ratio R (Eq. (1)), and the impact dimension is calculated as follows:

$$R=\ln(Xtreatment/Xcontrol) \quad (1)$$

where: X is the mean variable in the treatment and control groups, and the negative value of R refers to the shrinkage of the concentration of available P in the soil of the treatment group compared to the control group. Meanwhile, a positive value of R refers to an increase in the available P concentration in the treatment group compared to the control group.

The mean effect sizes and 95% confidence intervals (CI) were computed by constructing random-effect models with a maximum likelihood using OpenMEE software. The R response ratio was then adjusted to reflect the change in the soil's P concentration after implementing PSM. The replacement percentage (Eq. (2)) is based on the recommended percentage (Luo et al., 2019).

$$P=100*(-1 + \exp R) \quad (2)$$

Regarding the PSM treatment group, the difference between the control and the group was significant if the 95% CI generated in OpenMEE's software of change did not overlap with zero in the figures (Liu and Greaver, 2010). The primary univariate analysis method determines the relationship between a group's various covariates and their outcomes. For instance, before the experiment, the soil's pH level was divided into acid, slightly acid, neutral, and alkaline. The soil organic C was also classified into five classes: low, low, moderate, high, and very high. Then, the experimental sites were also divided into five groups based on their P availability: very low, low, moderate, high, and very high.

## Results

***The overall effect of PSM application on soil chemical properties***

Based on meta-analysis results, PSM addition significantly improved all soil chemical properties (e.g., av-P, av-K, soil N, soil pH, soil organic carbon, N-$NH_4$, N-$NO_3$, phosphatase, acid phosphatase, and alkaline phosphatase) were considered in the analysis (Figure 2; Table 2). PSM increased the solubility of phosphate and potassium in the soil by around 204.7% and 110.2%, respectively, compared to the control. PSM also increased the total N content in the soil, N-$NH_4$ and N-$NO_3$, by 70.6%, 36.4% and 164.3% respectively. PSM treatment also caused soil pH to decrease significantly by 173.8%, with SOC content increasing by 8.7% from the control. The phosphatase content increased significantly by 400.1%, with alkaline phosphatase and acid phosphatase increasing 20-fold each.

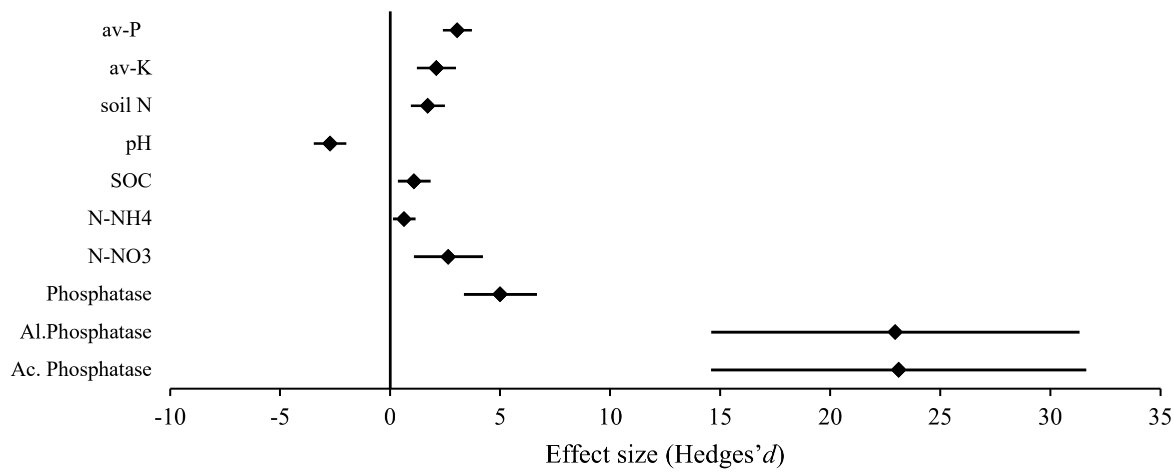


Figure 2. The total effect of PSM on soil available phosphate (Av-P), soil-available potassium (Av-K), soil N, soil pH, soil organic carbon (SOC), soil N-Ammonium (N-$NH_4$), soil N-Nitrate (N-$NO_3$), soil Phosphatase, soil Alkaline Phosphatase, a soil Acid phosphatase. The effect size was considered statistically significant if the 95% bootstrap confidence interval (CI) did not include zero.

***Soil available P***

This meta-analysis study shows that applying PSM to neutral soil (ES = 4.225; $p<0.001$) increases the effectiveness of PSM in dissolving soil P. P solubility is also influenced by the high organic matter content in the soil (ES = 10.033; $p<0.001$) with the very high P availability content in the soil (ES = 5.733; $p<0.001$). Meanwhile, PSM application on P solubility will increase when applied to soil with sandy loam texture (ES = 8.527; $p<0.001$) (Figure 3A).

Table 2. Summary of the effect size Hedges'*d* of soil chemical properties under different conditions.

| Response parameter | n | Effect size | Lower bound | Upper bound | Standard Error | p-value |
|---|---|---|---|---|---|---|
| Av-P | 104 | 3.047 | 2.389 | 3.706 | 0.336 | <0.001 |
| Av-K | 24 | 2.102 | 1.206 | 2.999 | 0.457 | < 0.001 |
| Soil N | 16 | 1.706 | 0.933 | 2.478 | 0.394 | < 0.001 |
| pH | 50 | -2.738 | -3.483 | -1.992 | 0.38 | < 0.001 |
| SOC | 20 | 1.087 | 0.35 | 1.825 | 0.376 | 0.004 |
| $N-NH_4$ | 11 | 0.636 | 0.132 | 1.139 | 0.257 | 0.013 |
| $N-NO_3$ | 11 | 2.643 | 1.074 | 4.213 | 0.801 | < 0.001 |
| Phosphatase | 24 | 5.001 | 3.347 | 6.655 | 0.844 | < 0.001 |
| Alkaline Phosphatase | 12 | 22.956 | 14.588 | 31.325 | 4.27 | < 0.001 |
| Acid Phosphatase | 12 | 23.104 | 14.573 | 31.636 | 4.353 | < 0.001 |

*significant changes when the 95% confidence interval of the effect size did not overlap with zero.

\

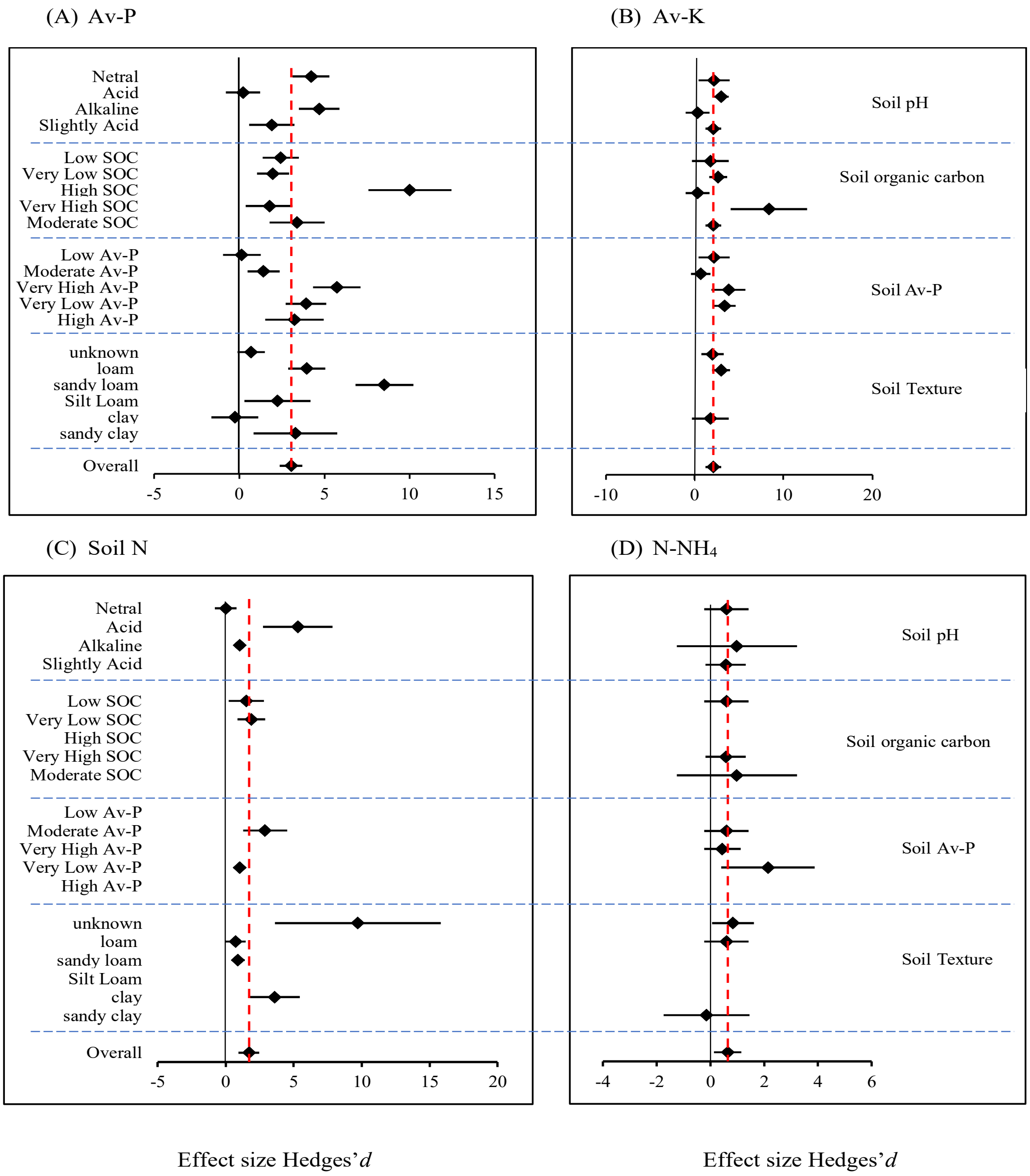


Figure 3. Effect size Hedges'*d* for the soil chemical properties (A) soil Available P(Av-P); (B) soil available K (Av-K); (C) soil nitrogen (soil N) and (D) soil ammonium ($N-NH_4$) to PSM addition in soil under different soil characteristics (soil pH, soil organic matter, soil available P, and soil texture). The effect size was considered statistically significant if the 95% bootstrap confidence interval did not include zero.

***Soil available K***

The addition of PSM had a significant effect on soil K availability (ES = 0.457; p<0.001), with the highest value obtained in acid soil pH conditions (ES = 2.972; p<0.001) with very high soil organic C content (ES = 8.366; p<0.001). The very high availability of soil P (ES = 3.824; p<0.001) with a loamy soil texture (ES = 2.986; p<0.001) also determines the significance of PSM application (Figure 3B).

***Soil total N***

Soil N increased with PSM culture as a treatment (1.706; p<0.001). PSM significantly reduced soil pH when applied to soil with acid pH (ES = 5.293; p<0.001). Apart from that, soil N also increased when PSM culture was given to soil with a very low SOC content (1.881; p<0.001) and moderate available P content (ES = 2.888; p<0.001) with a clay soil texture (ES = 3.603; p<0.001) (Figure 3C).

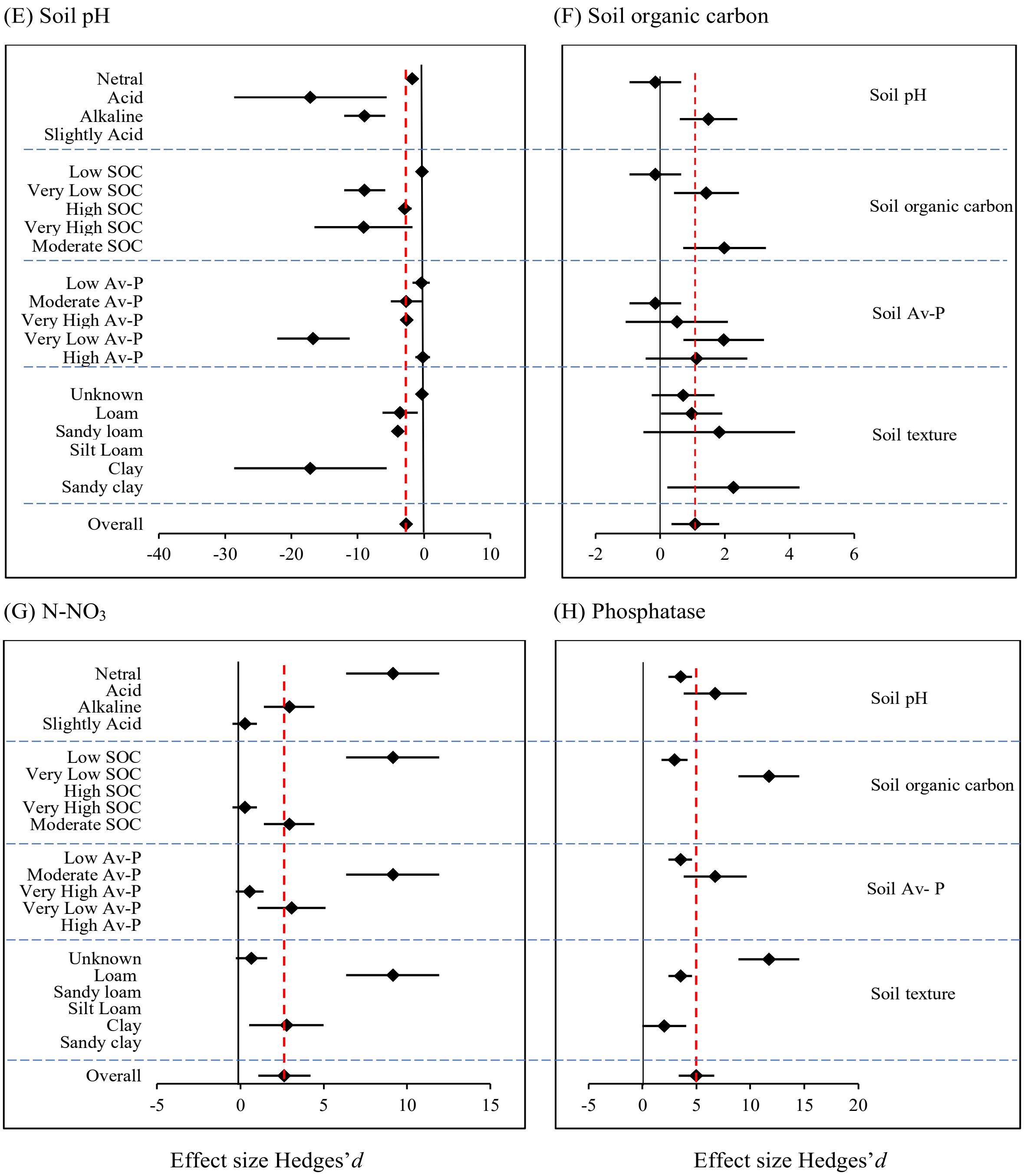


Figure 4. Effect size Hedges'*d* for the soil chemical properties (E) soil pH, (F) soil organic carbon; (G) soil $NO_3$; and (H) phosphatase to PSM addition in soil under different soil characteristics (soil pH, soil organic matter, soil available P, and soil texture). The effect size was considered statistically significant if the 95% bootstrap confidence interval did not include zero.

***Soil $NH_4$-N***

The $NH_4$-N value increased when PSM was applied to alkaline soil (ES = 0.971; p = 0.395), with moderate SOC content (ES = 0.971), very low available P content (ES = 2.138), soil texture with other classifications (ES = 0.832; P = p.038) (Figure 3D).

***Soil pH***

According to the study, the effect of PSM on the soil reduced soil pH (ES = -2.738; p<0.001). Soil pH significantly decreased when PSM was applied to soil that had acid characteristics (ES = -17.141; P = 0.003) with very low SOC content (ES = -8.965; p<0.001). PSM also lowered pH when applied to the soil with very low available P (ES = -16.709; p<0.001) (Figure 4E).

***Soil organic carbon***

PSM was able to significantly increase the SOC content in alkaline soil (ES =1.496; p<0.001). Application of PSM to soil increased SOC in soil with moderate SOC content (ES =1.985; p = 0.002) and very low available P content (ES = 1.971; p = 0.002). Applying PSM to soil with a sandy clay texture also increased SOC in sandy loam soil (ES = 2.271) (Figure 4F).

***Soil $NO_3$***

The study results revealed that PSM was able to increase the $NO_3$ content in the soil. PSM application increases $NO_3$ in soil with neutral pH (ES = 9.143; p<0.001), moderate available P content (ES = 9.143; p<0.001), and low sil SOC content (ES = 9.143; p<0.001) with a loamy texture (9.143; p<0.001) (Figure 4G).

***Soil phosphatase, acid phosphatase, and alkaline phosphatase***

Phosphatase in soil can also increase due to applying PSM to soil with acidic pH (ES = 6.748; p<0.001). In addition, phosphatase increased when PSM was applied to soil with moderate P content (ES = 6.748; p<0.001), very low SOC content (ES = 11.727; p<0.001), and with unknown soil texture (ES = 11.727; p<0.001) (Figure 4H). Acid phosphatase increased when PSM was applied to alkaline soil (ES = 26.562; p<0.001), with very low available P content (ES = 23.104; p<0.001), very low SOC content (ES = 23.104; p<0.001), with loam soil texture (ES = 41.436; p<0.001) (Figure 5I.). An increase also occurred in alkaline phosphatase in soil with alkaline conditions (ES=26.562), with low available P (ES = 22.956; p<0.001), very low SOC content (ES=22.956; p<0.001), with a loamy soil texture (ES = 41.436; p<0.001) (Figure 5J).

***Effect of PSM genus on soil***

The availability of P in the soil can increase significantly by providing the right microbes with the best capabilities. This study showed that the highest av-P was obtained by microbes from the genus *Penicillium* (ES = 8.272; p<0.001) (Figure 6K). Meanwhile, K solubility was obtained in the *Bulkhoderia* application (ES = 8.272) (Figure 6L).

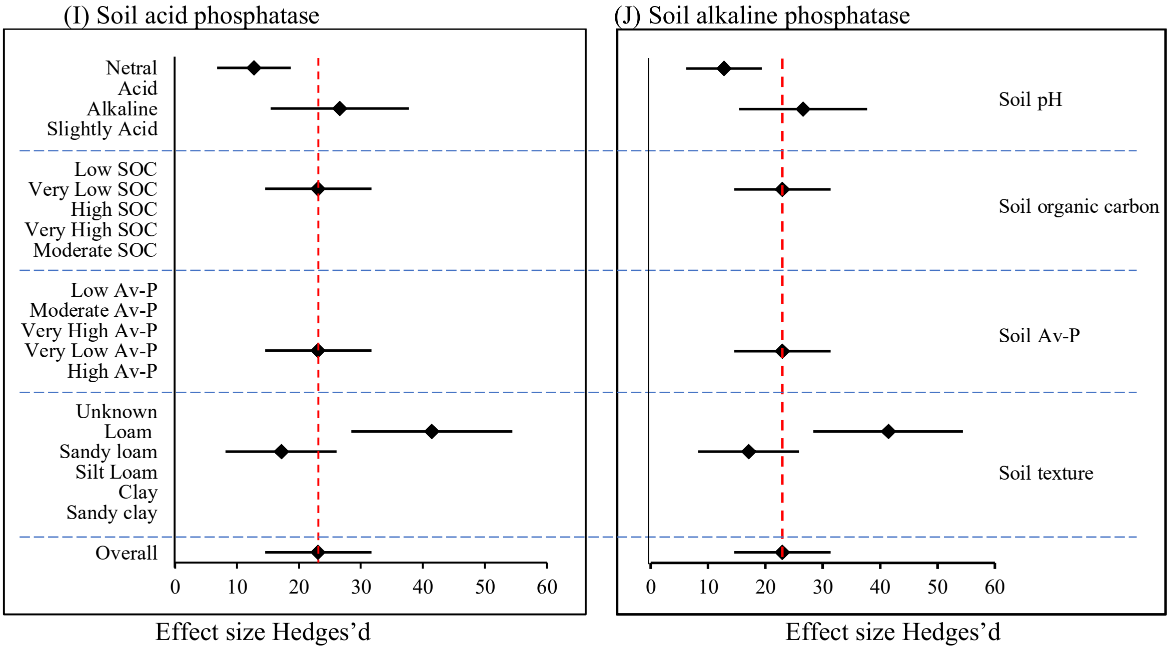


Figure 5. Effect size Hedges'*d* for the soil chemical properties (I) soil acid phosphatase and (J) soil alkaline phosphatase to PSM addition in soil under different soil characteristics (soil pH, soil organic matter, soil available P, and soil texture). The effect size was considered statistically significant if the 95% bootstrap confidence interval did not include zero.

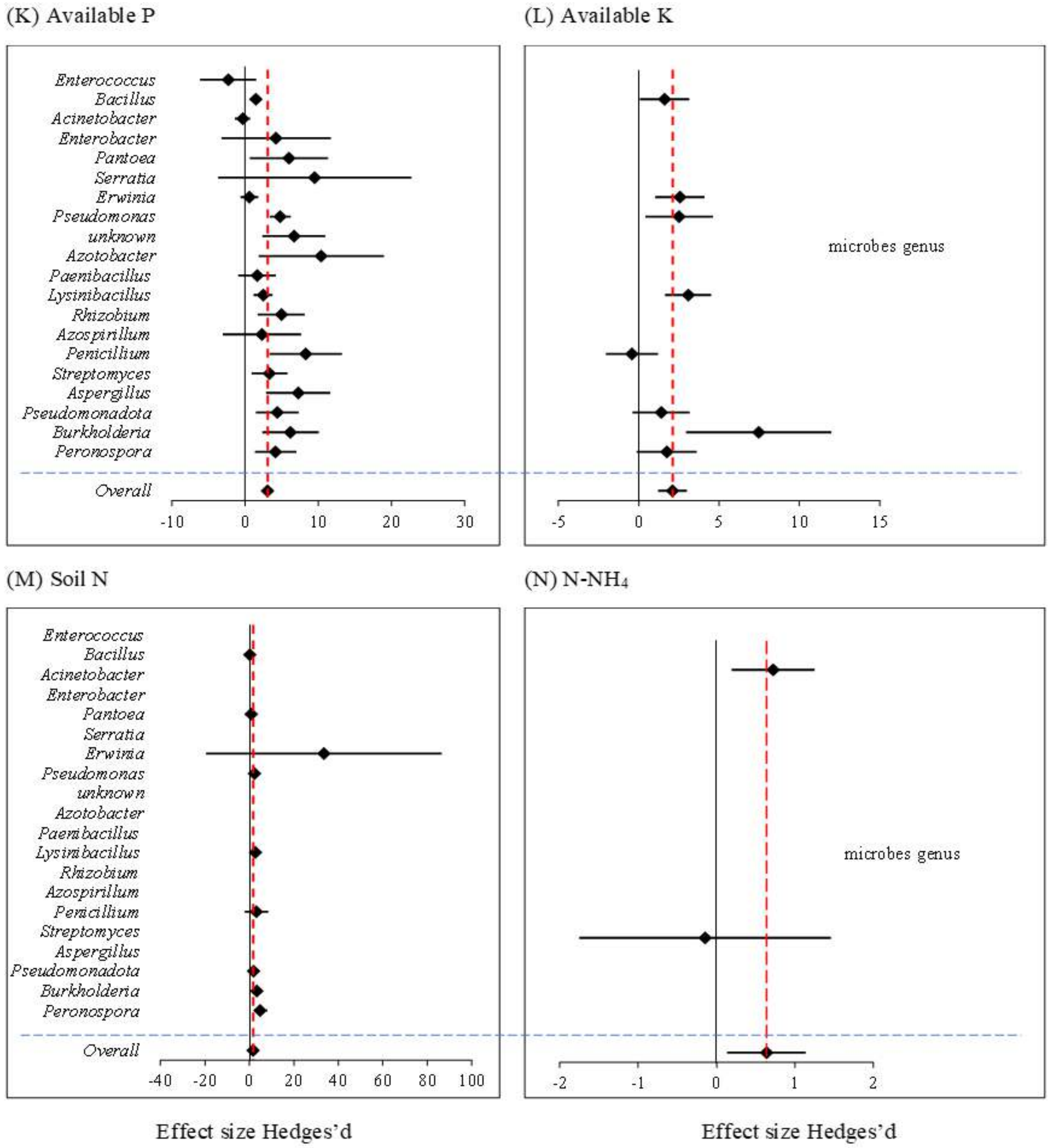


Figure 6. Effect size Hedges'*d* for the soil chemical properties (K) soil available P(Av-P); (L) soil available K (Av-K); (M) soil nitrogen (soil N) and (N) soil ammonium ($NH_4$) to PSM addition in agriculture soil with different soil microbes genus. The effect size was considered statistically significant if the 95% bootstrap confidence interval did not include zero.

The highest total soil N was obtained by *Peronospora* microbes (ES = 4.878) (Figure 6M). Soil pH decreased when treated with *Pseudomonadota* (ES = -32.801) (Figure 7O). *Pantoea* microbes could increase SOC (ES=4.749; p = 0.042) (Figure 7P), while *Bacillus* microbes could increase $NH_4$ (ES = 0.721; p = 0.008) (Figure 6N) and $NO_3$ (2.694; p=0.002) (Figure 7Q). Phosphatase content was increased by *Erwinia* microbes (ES = 11.786; p<0.001) (Figure 7R), while alkaline phosphatase and acid phosphatase were increased by *Pseudomonas* (ES = 42.375; p<0.001; ES = 42.375; p<0.001) (Figures 8S and 8T).

### *Effect of crop types on soil chemical properties*

The results of this study showed that the highest increase in P availability was obtained when PSM was given to tomato plants (ES = 10.033; p<0.001) (Figure 9U). At the same time, the highest K availability was obtained when PSM was given to cabbage (ES = 8.366; p<0.001) (Figure 9V). The highest soil N was obtained from bean plants (ES = 8.617; p<0.001) (Figure 9W). Meanwhile, the highest $NH_4$-N was obtained from cabbage plants (ES = 2.138; p<0.001) (Figure 9X).

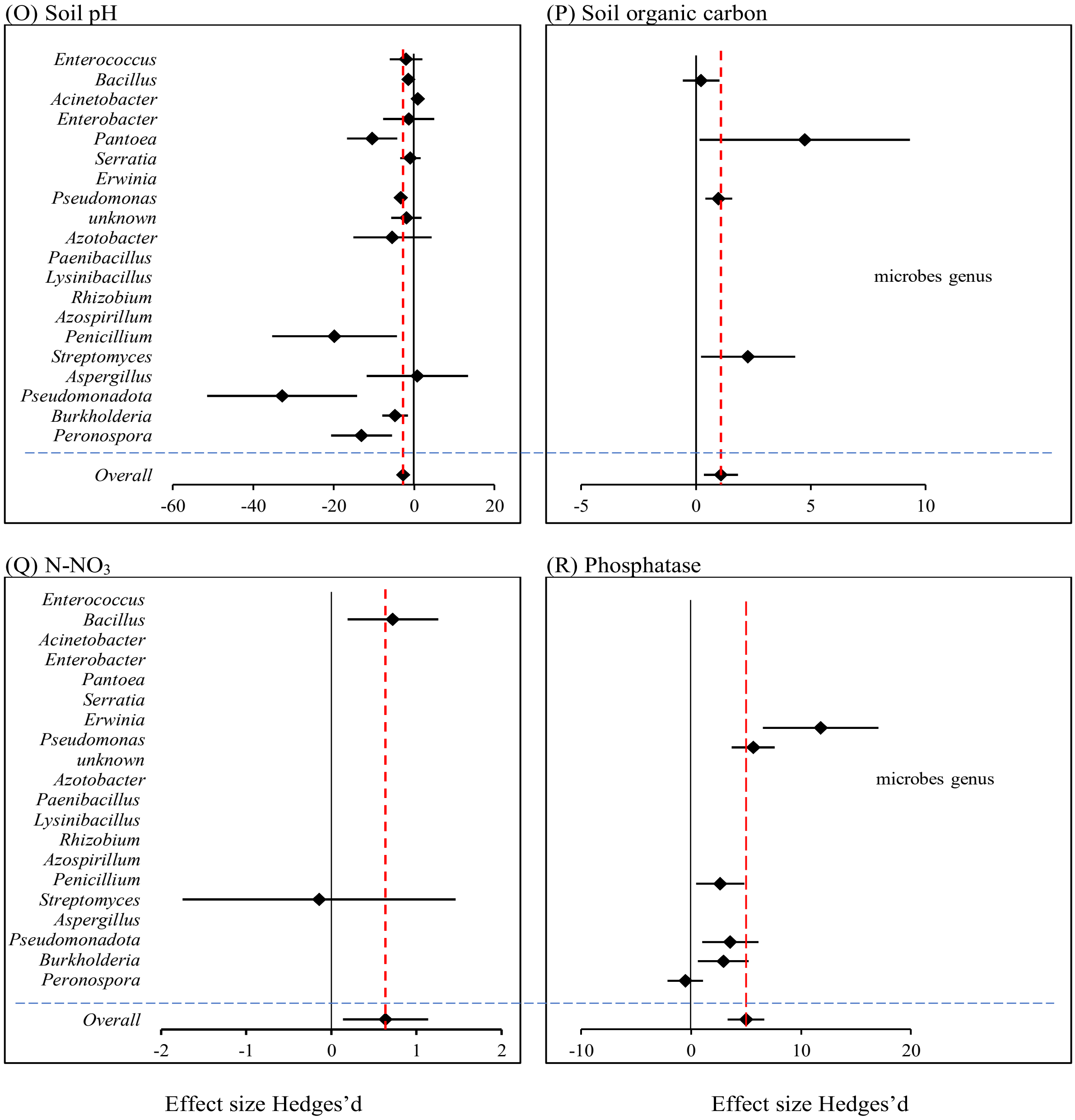


Figure 7. Effect size Hedges'*d* for the soil chemical properties (O) soil pH; (P) soil organic carbon; (Q) soil $NO_3$ and (R) soil phosphatase to PSM addition in agriculture soil with different soil microbes genus. The effect size was considered statistically significant if the 95% bootstrap confidence interval did not include zero.

## Discussions

Soil pH is a representative indicator of soil characteristics when assessing P availability. In soil with a neutral pH, soil elements are generally more available, including soil P (Elbasiouny et al., 2020). P ions in soil are usually available as $H_2PO_4$ and $HPO_4$. P element is one of the macro elements plants need to support their growth. PSM can make P bound in the soil more available to plants through various mechanisms because, generally, P is strongly bound to other elements such as Fe, Al, Ca, and Mg. The release of organic acids and soil enzymes by PSM is thought to be the main cause of increased P availability in the soil (Tian, 2021). The current study revealed decreased soil pH after giving PSM culture. PSMs produce various types of organic acids due to their metabolic activity. Organic acids, such as lactic acid, acetic acid, or citric acid, can lower soil pH. The decreased soil pH makes the soil environment more acidic, which can increase the solubilization of insoluble mineral phosphates. Some mineral phosphates tend to be more soluble in acidic pH. Organic acids have a carboxyl acid group (-COOH) in their structure, which can form complex bonds with phosphate ions ($PO_4^{3-}$). Phosphate bound in complex bonds with organic acids is more easily released into the soil solution (Pokhrel et al., 2019). The moderator variable shows that soil with a high organic matter content plays a role in dissolving P in the soil given PSM (Tian, 2021).

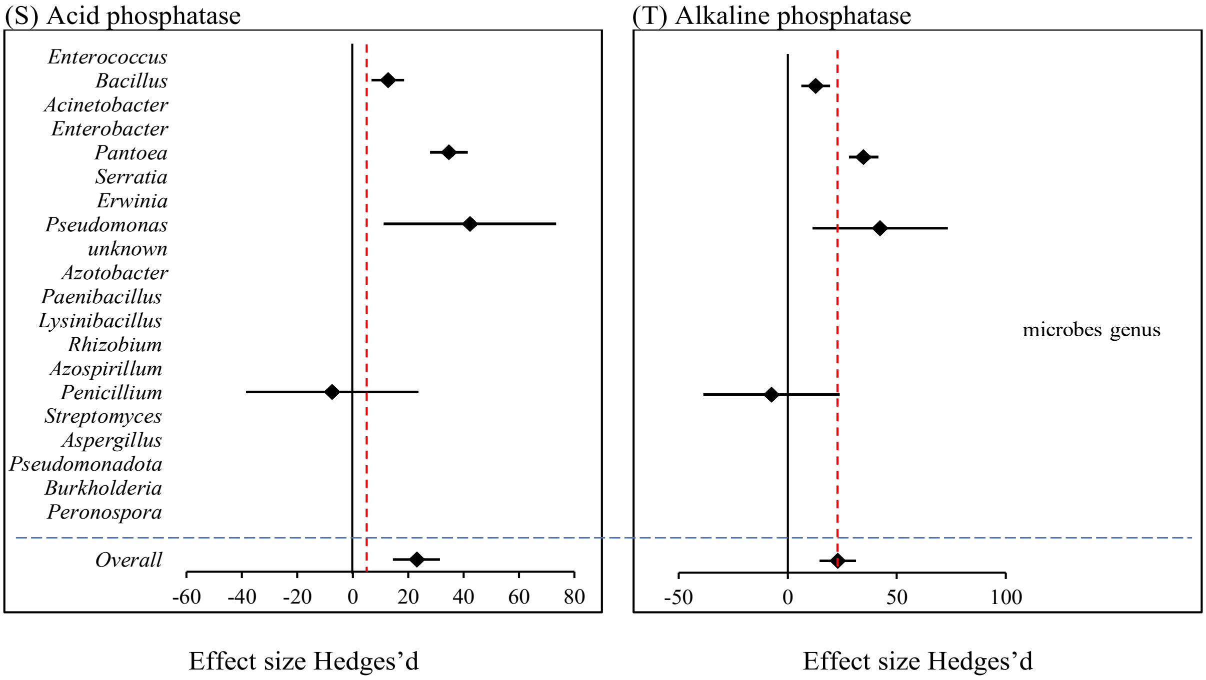


Figure 8. Effect size Hedges'*d* for the soil chemical properties (S) soil acid phosphatase and (T) alkaline phosphatase to PSM addition in different soil microbes genus. The effect size was considered statistically significant if the 95% bootstrap confidence interval did not include zero.

Indirectly, soil organic matter increases PSM activity by supplying carbon for microbial metabolism in the soil. Microbes need sufficient carbon to live well before functioning in the soil. This study follows (Goswami et al., 2019) research that organic materials also help increase the effectiveness of PSM in dissolving phosphate. Apart from contributing carbon, the complete decomposition of organic matter also provides other elements that PSM needs to increase its activity in the soil. Soils that naturally have high P availability also have a significant effect in increasing P availability as a result of PSM application. This condition is natural because PSM is believed to require little effort to increase P availability in the soil. An environment that has good P characteristics will support PSM in living better. PSM is also thought to need P to support its life and activities. Therefore, PSM's ability to dissolve phosphate may be because PSM needs phosphate (Tian, 2021). When applying PSM, phosphate solubility also increases in soil with a sandy loam texture. Soils with a sandy loam texture are soil textures commonly found in fertile soil (Simonsson et al., 2018). So, it supports PSM activities in increasing available P.

Apart from P, it turns out that PSM can dissolve K in the soil (El Attar et al., 2022). The addition of PSM significantly affects soil K availability, with the highest value obtained in acid soil pH with very high C-organic content and very high initial P availability with loam soil texture. The characteristics of K are almost the same as those of P, which is difficult to dissolve. Some PSMs can dissolve potassium, and the same mechanism is thought to be due to the release of K ions from soil colloidal complexes due to the released organic acids. Even though it may not be as much P, the function of PSM in dissolving K is important to consider as a multifunctional biofertilizer ingredient (Rani and Sengar, 2020).

The highest effect size on soil N due to PSM application was obtained in acidic soil pH with low organic C content. The availability of nitrogen (N) in acid soil (low pH) can be influenced by several factors. Accurately measuring N in soil is actually difficult because the nature of N in soil is easily leached and volatile. However, these meta-analysis results indicate that PSM can increase N in the soil even under acidic conditions. The clay texture gives a soil effect size N value above the overall effect size value, even though soil with an unknown texture gives the highest soil effect size N value. Clay particles also can hold nutrients, including nitrogen. In clay soils, nitrogen tends to remain locked up in a form that is not immediately available to plants (Clark et al., 2019).

The effect size of soil ammonium due to PSM treatment shows values that are not significantly different in various soil pH, C-organic content, and soil texture. Ammonium only shows high values in soils with very low P availability. Ammonium is a form of N that plants can absorb. Its presence in soil is the same as other cations that have the potential to bind to soil colloids. So, the mechanism for releasing $NH_4$ in the soil is the same as other cations (Daniel et al., 2020). These processes interact with various environmental factors, including temperature, humidity, soil pH, and microbial activity, which can influence the rate and availability of ammonium in the soil (Daniel et al., 2020). The application of PSM to acidic soil causes a decrease in pH from soil that has an acidic pH to an alkaline pH. Soil pH decreased most sharply when PSM was applied at an acidic pH. Many studies state that PSM releases organic acids, which may cause decreasing soil pH (Zúñiga-Silgado et al., 2020). Application of PSM to soil with low to high organic C also causes a significant decrease in pH. These results showed that soil organic matter and PSM application contribute to organic acid in the soil.

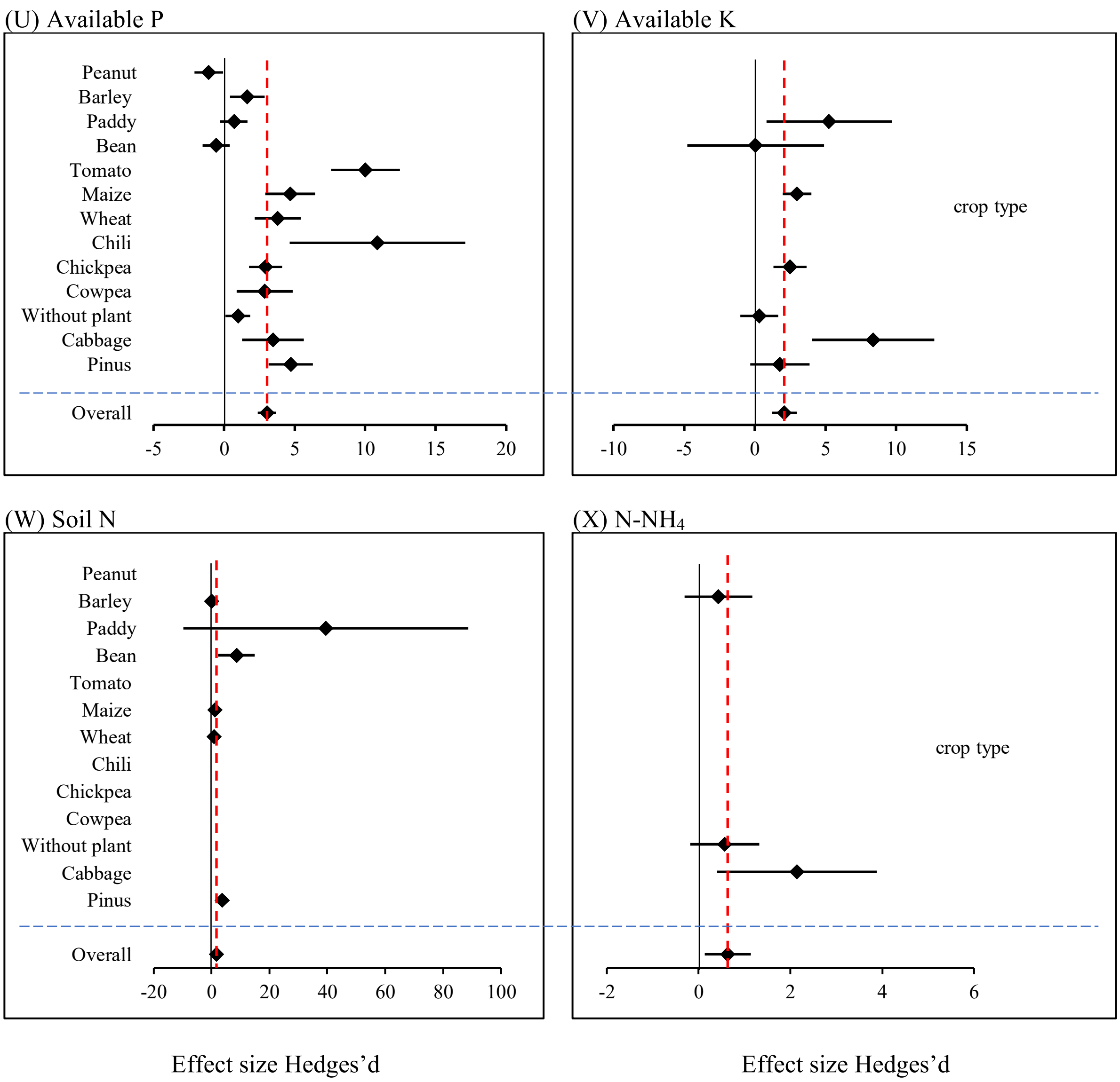


Figure 9. Effect size Hedges'd for the soil chemical properties Av-P (U), Av-K (V), Soil N (W), $NH_4$ (X) to PSM addition in different crop types. The effect size was considered statistically significant if the 95% bootstrap confidence interval did not include zero.

The highest decrease in pH also occurs when PSM is applied to the soil with low P. Low P availability is usually found in soils with an acid pH. Applying PSM to soil with a clay texture can reduce soil pH significantly. Soil with a clay texture is also soil that is often found in acid pH conditions. Soil acidity is caused by an abundance of $H^+$ ions, one of which is caused by Al and Fe ions. Aluminum ions ($Al^{3+}$) release hydrogen ions ($H^+$) when interacting with water in the soil. This condition occurs in the reaction: $Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$. Iron in the form of ferrous ($Fe^{2+}$) or ferric ($Fe^{3+}$) can also contribute to increasing soil acidity. When iron ions are oxidized in soil, the following reaction occurs $4Fe^{2+} + O_2 + 6H_2O \rightarrow 4Fe(OH)_3 + 8H^+$ (Oburger et al., 2020).

The meta-analysis results showed that PSM application significantly increases soil organic matter. This condition is due to increased PSM microbial activity in the soil. Microbes have an important role in increasing organic carbon levels in the soil. This process is known as organic carbon sequestration in soil, which refers to the increased accumulation of organic carbon in dead organic matter or organic compounds. As is known, SOC comes from microbial cells, soil organism remains, and plant residues (Liang et al., 2019). The highest increase in SOC due to the addition of PSM occurred in alkaline soil, and it is suspected that PSM grows better in alkaline soil. The principal agents in soil organic carbon sequestration are soil microorganisms, particularly through the buildup of their necromass.

PSMs have an organic carbon component in the form of their biomass. When microbes live and reproduce, they take up carbon from organic sources in the soil and store it in their bodies. When microbes die, their biomass can contribute to soil organic carbon (Camenzind et al., 2023). PSM increases SOC when applied to soil with moderate natural SOC content. SOC with medium levels increases further when POC is added, while high SOC does not increase too much, presumably because the levels are already saturated. Low P content encourages microbes to increase their growth so that the residue increases SOC in the soil. At the same time, sandy loam texture is a good condition when PSM is applied to the soil so that the SOC increases.

The highest effect size on soil nitrate was obtained at neutral soil pH. The nitrate ($NO_3^-$) content in soil at neutral pH (around pH 7) can vary depending on various factors, including soil type, agricultural practices, and climate. In general, neutral pH is a condition that supports the availability of nitrate in the soil because neutral pH is the optimal condition for cation exchange and microbial activity involved in the nitrogen cycle (Albina et al., 2019). PSM is suspected of having the ability, like microbes, to oxidize ammonium ($NH_4^+$) to nitrate ($NO_3^-$) and is more active at neutral pH. Low to moderate organic matter showed an increase in $NO_3$ after being added by PSM. This study also showed that a loamy soil texture is the optimum condition for PSM to increase $NO_3$ in the soil. Loam soil has a balanced soil texture of sand, silt, and silt, giving it several beneficial properties for the microbes.

PSM plays an important role in the phosphorus cycle in ecosystems and can influence the activity of the phosphatase enzyme (Tian, 2021). The study results show that adding PSM to the soil can increase phosphatase significantly. The highest increase in phosphatase was obtained when PSM was applied to soil with an acidic pH. The highest phosphatase was obtained in soil with an acid pH, with very low SOC, low P availability, and soil texture in the unknown soil texture category. Phosphatase enzyme activity in acid soil generally decreases at very low pH. This study showed that apart from neutral pH, PSM is also able to increase phosphatase activity significantly at low pH. The phosphatase enzyme in acid soil can be influenced by various factors, one of which is the ability of PSM to produce and release this enzyme. Apart from that, organic materials can also influence the phosphatase content in the soil (Goswami et al., 2019). The results showed that the highest increase in phosphatase levels was shown in soil with very low SOC when compared to soil with low SOC content. The decomposition of organic materials by microbes produces phosphatase enzymes as part of the process. Moderate levels of available soil P content also stimulate the increase in phosphatase in soil. In loam soil textures, PSM can increase soil phosphatase content better than clay textures. Loam soil has good nutrient availability capacity because its fine particles can retain nutrients for longer and prevent the leaching of nutrients (Alkharabsheh et al., 2021). Acid and alkaline phosphatase in this study were also found to increase, especially in alkaline and neutral soils. This shows that PSM is able to adapt to soils with different pH levels. Microbes can respond to changes in soil pH by changing the composition of their cell membranes. This can help maintain membrane stability and cell integrity under different pH conditions.

PSM from the bacterial and fungal groups have very good abilities in dissolving soil P. This study shows that fungi from the *Aspergillus* and *Penicillium* groups have the highest ability to increase the solubility of phosphate in the soil, while the bacteria from the *Azotobacter* and *Serratia* groups. The solubility of P in the soil is much increased when microbes in fungal groups such as *Aspergillus* and *Penicillium* are applied (Hellal et al., 2019). This meta-analysis study also shows that bacteria from the *Bulkhoderia* group increase the highest K solubility in soil. In contrast, *Peronospora* shows the highest soil N, and *Bacillus* is the highest for $NH_4$. *Pseudomonadota* and *Penicillium* microbes showed the highest decrease in pH in the soil. This shows that decreasing pH does not always increase soil P solubility. *Pantoea* and *Streptomyces* treatments can increase the highest SOC, while *Bacillus* application increases the highest $NO_3$.

Bacteria from the *Erwinia* group produce the highest phosphatase and alkaline phosphatase enzymes, while *Pseudomonas* and *Pantoea* bacteria produce the highest acid phosphatase. The ability of microbes to fix nitrogen (N) and dissolve phosphate (P) in soil varies. The type of microbe, microbial species, and the soil environment where it is active can determine the extent of the microbe's ability to improve soil properties (Goswami et al., 2019). The ability of each microbe in the soil will determine the status of the nutrients in the soil so that it will affect the properties of the soil as a whole. As is known, soil properties will determine the growth of plants and other organisms in the soil ecosystem.

Different soil nutrient contents will respond differently to plants. So, one of the keys to increasing soil productivity and soil properties on agricultural land is choosing the right biological fertilizer. This study shows that the greatest response to P availability was obtained when PSM was applied to soil with tomato and chili plants. Meanwhile, cabbage and rice gave the highest response to K availability due to PSM administration. Bean plants gave the highest response to soil N due to PSM application. Meanwhile, the response of cabbage plants was highest to $NH_4$ from the PSM given. The results of this meta-analysis show that the challenge ahead is how to create biofertilizers that are suitable for many plants and soils.

## Conclusions

Soil pH, SOC, and texture greatly influence the availability of phosphorus (P) in the soil. P is fixed and becomes unavailable to plants in alkaline pH (pH>7.5) and acid soil (pH<6). Various phosphate solubilization mechanisms by PSM can be used to convert P in soil from unavailable to available form. The ability of PSM to dissolve P effectively varies greatly and depends on soil conditions, such as pH, organic matter content, and P availability. Environmental factors can limit the effectiveness of PSM as a biofertilizer in dissolving soil phosphate. This meta-analysis shows that in terms of phosphate solubility, PSM is more effective on alkaline soils with high SOC content, high P availability, and sandy loam texture. PSM is more effective in dissolving K in soil with an acid pH that has very high SOC, very high available P, and a loamy soil texture. The highest increase in soil N was obtained when PSM was applied to soil with characteristics of acid pH, very low SOC, moderate available P, and loamy texture. The results of this meta-analysis showed that bacteria from the genus Azotobacter obtained the highest ability to leach phosphate, while fungi obtained it from the genus Penicillium. The highest K solubility was obtained in the genus Burkholderia, while an effective increase in soil N was shown when PSM was given to the genus Peronospora.

## Acknowledgments

The authors are sincerely grateful to all the scientists whose data and input were incorporated into this meta-analysis. Additionally, the authors thank the following people for their contributions to this study: Anggi Nico Flatian, Teguh Wahyono, Beni Ernawan, and Dyah Marganingrum.

## References

Albina, P., Durban, N., Bertron, A., Albrecht, A., Robinet, J.C. and Erable, B. 2019. Influence of hydrogen electron donor, alkaline pH, and high nitrate concentrations on microbial denitrification: A review. *International Journal of Molecular Sciences* 20(20), doi:10.3390/ijms20205163.

Alkharabsheh, H.M., Seleiman, M.F., Battaglia, M.L., Shami, A., Jalal, R.S., Alhammad, B.A., Almutairi, K.F. and Al-Saif, A.M. 2021. Biochar and its broad impacts in soil quality and fertility, nutrient leaching, and crop productivity: A review. *Agronomy* 11(5), doi:10.3390/agronomy11050993.

Anzuay, M.S., Ludueña, L.M., Angelini, J.G., Fabra, A. and Taurian, T. 2015. Beneficial effects of native phosphate solubilizing bacteria on peanut (*Arachis hypogaea* L.) growth and phosphorus acquisition. *Symbiosis* 66:89-97, doi:10.1007/s13199-015-0337-z.

Aqeel, M., Ran, J., Hu, W., Irshad, M.K., Dong, L., Akram, M.A., Eldesoky, G.E., Aljuwayid, A.M., Chuah, L.F. and Deng, J. 2023. Plant-soil-microbe interactions in maintaining ecosystem stability and coordinated turnover under changing environmental conditions. *Chemosphere* 318(October 2022):137924, doi:10.1016/j.chemosphere.2023.137924.

Barlog, P., Hlisnikovský, L. and Kunzová, E. 2020. Effect of digestate on soil organic carbon and plant-available nutrient content compared to cattle slurry and mineral fertilization. *Agronomy* 10(3), doi:10.3390/agronomy10030379.

Camenzind, T., Mason-Jones, K., Mansour, I., Rillig, M.C. and Lehmann, J. 2023. Formation of necromass-derived soil organic carbon determined by microbial death pathways. *Nature Geoscience* 16(2):115-122, doi:10.1038/s41561-022-01100-3.

Canbolat, M.Y. 2006. Effect of plant growth-promoting bacteria and soil compaction on barley seedling growth, nutrient uptake, soil properties, and rhizosphere microflora. *Biology and Fertility of Soils* 42(4):350-357, doi:10.1007/s00374-005-0034-9.

Chouyia, F.E., Romano, I. and Fagnano, M. 2020. P-solubilizing *Streptomyces roseocinereus* MS1B15 with multiple plant growth-promoting traits enhance barley development and regulate rhizosphere microbial population. *Frontiers in Plant Science* 11(August):1-10, doi:10.3389/fpls.2020.01137.

Clark, M., Hastings, M. G., and Ryals, R. 2019. Soil carbon and nitrogen dynamics in two agricultural soils amended with manure-derived biochar. *Journal of Environmental Quality* 48(3), 727-734, doi:10.2134/jeq2018.10.0384

Daniel, G., Bohn, H.L., Connor, G.A.O. and Wiley, J. 2020. *Soil Chemistry*. John Wiley and Sons.

Duarah, I., Deka, M., Saikia, N. and Boruah, H.P.D. 2011. Phosphate solubilizers enhance NPK fertilizer use efficiency in rice and legume cultivation. *3 Biotech* 1:227-238, doi:10.1007/s13205-011-0028-2.

El Attar, I., Hnini, M., Taha, K. and Aurag, J. 2022. Phosphorus availability and its sustainable use. *Journal of Soil Science and Plant Nutrition* 22(4):5036-5048, doi:10.1007/s42729-022-00980-z.

Elbasiouny, H., Elbehiry, F., El-Ramady, H. and Brevik, E.C. 2020. Phosphorus availability and potential environmental risk assessment in alkaline soils. *Agriculture (Switzerland)* 10(5):1-18, doi:10.3390/agriculture10050172.

Fatima, F., Ahmad, M.M., Verma, S.R. and 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, doi:10.1007/s13762-021-03425-9.

Fitriatin, B.N., Sofyan, E.T. and Turmuktini, T. 2021. Increasing soil P and yield of upland rice through application phosphate solubilizing microbes. *Haya Saudi Journal of Life Sciences* 6(7):163-167, doi:10.36348/sjls.2021.v06i07.007.

Fitriatin, B.N., Suryatmana, P., Yuniarti, A. and Istifadah, N. 2017. The application of phosphate solubilizing microbes biofertilizer to increase soil P and yield of maize on Ultisols Jatinangor. *KnE Life Sciences* 2(6):179, doi:10.18502/kls.v2i6.1037

Goswami, S.P., Dubey, A.N, Singh, N.K. and Maurya, B. 2019. Role of phosphorus solubilizing microorganisms and dissolution of insoluble phosphorus in soil.

*International Journal of Chemical Studies* 7(3):3905-3913.

Gurmu, G. 2019. Soil organic matter and its role in soil health and crop productivity improvement. *Academic Research Journal* 7(7):475-483, doi:10.14662/ARJASR2019.147.

Haddaway, N.R., Page, M.J., Pritchard, C.C. and McGuinness, L.A. 2022. PRISMA2020: An R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and open synthesis. *Campbell Systematic Reviews* 18(2):1-12, doi:10.1002/cl2.1230.

Hariprasad, P. and Niranjana, S.R. 2009. Isolation and characterization of phosphate solubilizing rhizobacteria to improve plant health of tomato. *Plant and Soil* 316:13-24, doi:10.1007/s11104-008-9754-6.

Hellal, F., El-Sayed, S., Zewainy, R. and Amer, A. 2019. Importance of phosphate pock application for sustaining agricultural production in Egypt. *Bulletin of the National Research Centre* 43(1), doi:10.1186/s42269-019-00509.

Herre, M., Heitkötter, J., Heinze, S., Rethemeyer, J., Preusser, S., Kandeler, E. and Marschner, B. 2022. Differences in organic matter properties and microbial activity between bulk and rhizosphere soil from the top- and subsoils of three forest stands. *Geoderma* 409, doi:10.1016/j.geoderma.2021.115589.

Islam, M.K., Sano, A., Majumder, M.S.I., Sakagami, J.I., Gima, S. and Hossain, M.A. 2019. Evaluation of organic acid production potential of phosphate solubilizing fungi isolated from soils in Okinawa, Japan. *Applied Ecology and Environmental Research* 17(6):15191-15201, doi:10.15666/aeer/17061519115201.

Joe, M.M., Deivaraj, S., Benson, A., Henry, A.J. and Narendrakumar, G. 2018. Soil extract calcium phosphate media for screening of phosphate-solubilizing bacteria. *Agriculture and Natural Resources* 52(3):305-308, doi:10.1016/j.anres.2018.09.014.

Kaur, G. and Reddy, M.S. 2014. Role of phosphate-solubilizing bacteria in improving the soil fertility and crop productivity in organic farming. *Archives of Agronomy and Soil Science* 60(4):549-564, doi:10.1080/03650340.2013.817667.

Kaur, G. and Reddy, M.S. 2015. Effects of phosphate-solubilizing bacteria, rock phosphate and chemical fertilizers on maize-wheat cropping cycle and economics. *Pedosphere* 25(3):428-437, doi:10.1016/S1002-0160(15)30010-2.

Khan, M.S., Zaidi, A., Ahemad, M., Oves, M. and Wani, P.A. 2010. Plant growth promotion by phosphate solubilizing fungi - Current perspective. *Archives of Agronomy and Soil Science* 56(1):73-98, doi:10.1080/03650340902806469.

Kolodiazhnyi, O.I. 2021. Phosphorus compounds of natural origin: Prebiotic, stereochemistry, application. *Symmetry* 13(5), doi:10.3390/sym13050889.

Kudoyarova, G.R., Vysotskaya, L.B. and Arkhipova, T.N. 2017. Effect of auxin producing and phosphate solubilizing bacteria on mobility of soil phosphorus, growth rate, and P acquisition by wheat plants. *Acta Physiologiae Plantarum* 1-8, doi:10.1007/s11738-017-2556-9.

Kumar, A., Maurya, B.R. and Jha, S. 2014. In vitro solubilization of rock phosphate by fungus isolated from agricultural in vitro solubilization of rock phosphate by fungus isolated from agricultural soil. *RAU Journal of Research* 24:39-48, doi:10.13140/RG.2.2.27953.86880.

Liang, C., Amelung, W., Lehmann, J. and Kästner, M. 2019. Quantitative assessment of microbial necromass contribution to soil organic matter. *Global Change Biology* 25(11):3578-3590, doi:10.1111/gcb.14781.

Linu, M.S., Asok, A.K., Thampi, M., Sreekumar, J., Jisha, M.S., Asok, A.K., Thampi, M., Sreekumar, J. and Jisha, M.S. 2019. Plant growth promoting traits of indigenous phosphate solubilizing *Pseudomonas aeruginosa* isolates from chilli (*Capsicum annuum* L.) rhizosphere. *Communications in Soil Science and Plant Analysis* 50(4):1-14, doi:10.1080/00103624.2019.1566469.

Liu, L. and Greaver, T.L. 2010. A global perspective on belowground carbon dynamics under nitrogen enrichment. *Ecology Letters* 13:819-828, doi:10.1111/j.1461-0248.2010.01482.x.

Liu, Z., Li, Y.C., Zhang, S., Fu, Y., Fan, X., Patel, J.S. and Zhang, M. 2015. Characterization of phosphate-solubilizing bacteria isolated from calcareous soils. *Applied Soil Ecology* 96(November):217-224, doi:10.1016/j.apsoil.2015.08.003.

Luo, G., Sun, B., Li, L., Li, M., Liu, M., Zhu, Y., Guo, S. and Ling, N. 2019. Understanding how long-term organic amendments increase soil phosphatase activities : Insight into phoD - and phoC -harboring functional microbial populations. *Soil Biology and Biochemistry* 139(October), doi:10.1016/j.soilbio.2019.107632.

Martins, J.D.L., Soratto, R.P., Fernandes, A.M. and Dias, P.H.M. 2018. Phosphorus fertilization and soil texture affect potato yield. *Revista Caatinga* 31(3):541-550, doi:10.1590/1983-21252018v31n302rc.

Martyniuk, S., Jończyk, K. and Kozieł, M. 2019. Phosphate solubilizing microorganisms and phosphatase activities in the rhizosphere soil of organically grown winter wheat cultivars. *Journal of Elementology* 24(2):461-471, doi:10.5601/jelem.2018.23.3.1678.

Naveed, M., Mehboob, I., Shaker, M.A., Hussain, M.B. and Farooq, M. 2015. Biofertilizers in Pakistan: Initiatives and limitations. *International Journal of Agriculture and Biology* 17(3):411-420, doi:10.17957/IJAB/17.3.14.672.

Oburger, E., Vergara Cid, C., Schwertberger, D., Roschitz, C. and Wenzel, W.W. 2020. Response of tungsten (W) solubility and chemical fractionation to changes in soil pH and soil aging. *Science of the Total Environment* 731:139224, doi:10.1016/j.scitotenv.2020.139224.

Patel, D.K., Archana, G. and Kumar, G.N. 2008. Variation in the nature of organic acid secretion and mineral phosphate solubilization by Citrobacter sp. DHRSS in the presence of different sugars. *Current Microbiology* 56(2):168-174, doi:10.1007/s00284-007-9053-0.

Penn, C.J., and Camberato, J.J. 2019. A critical review on soil chemical processes that control how soil ph affects phosphorus availability to plants. *Agriculture (Switzerland)* 9(6):1-18, doi:10.3390/agriculture9060120.

Perraud, Q., Cantero, P., Roche, B., Gasser, V., Normant, V.P., Kuhn, L., Hammann, P., Mislin, G.L.A., Ehret-Sabatier, L. and Schalk, I.J. 2020. Phenotypic adaption of Pseudomonas aeruginosa by hacking siderophores produced by other microorganisms. *Molecular and Cellular Proteomics* 19(4):589-607, doi:10.1074/mcp.RA119.001829.

Plaxton, W.C. and Tran, H.T. 2011. Metabolic adaptations of phosphate-starved plants. *Plant Physiology* 156(3):1006-1015, doi:10.1104/pp.111.175281.

Pokhrel, M.R., Poudel, B.R., Aryal, R.L., Paudyal, H. and Ghimire, K.N. 2019. Removal and recovery of phosphate from water and wastewater using metalloaded agricultural waste-based adsorbents: A review. *Journal of Institute of Science and Technology* 24(1):77-89, doi:10.3126/jist.v24i1.24640.

Rafique, M., Sultan, T., Ortas, I. and Chaudhary, H.J. 2017. Enhancement of maize plant growth with inoculation of phosphate-solubilizing bacteria and biochar amendment in soil. *Soil Science and Plant Nutrition* 63(5):460-469, doi:10.1080/00380768.2017.1373599.

Rani, V. and Sengar, R.S. 2020. Use of potassium bio-fertilizers technology for sustainable agriculture in dry areas. *Journal of Pharmacognosy and Phytochemistry* 9(6):1944-1946.

Santana, E. 2016. Effects of phosphate-solubilizing bacteria, native microorganisms, and rock dust on *Jatropha curcas* L. growth. *Genetics and Molecular Research* 15(4), doi:10.4238/gmr.15048729.

Simonsson, M., Östlund, A., Renfjäll, L., Sigtryggsson, C., Börjesson, G. and Kätterer, T. 2018. Pools and solubility of soil phosphorus as affected by liming in long-term agricultural field experiments. *Geoderma* 315(January 2017):208-219, doi:10.1016/j.geoderma.2017.11.019.

Singh, H. and Reddy, M.S. 2011. Effect of inoculation with phosphate solubilizing fungus on growth and nutrient uptake of wheat and maize plants fertilized with rock phosphate in alkaline soils. *European Journal of Soil Biology* 47(1):30-34, doi:10.1016/j.ejsobi.2010.10.005.

Singh, O., Gupta, M., Mittal, V., Kiran, S., Nayyar, H., Gulati, A. and Tewari, R. 2013. Novel phosphate solubilizing bacteria *Pantoea cypripedii* PS1 along with *Enterobacter aerogenes* PS16 and *Rhizobium ciceri* enhance the growth of chickpea (*Cicer arietinum* L.). *Plant Growth Regulation* 73(1), doi:10.1007/s10725-013-9869-5.

Swain, M.R., Laxminarayana, K. and Ray, R.C. 2012. Phosphorus solubilization by thermotolerant *Bacillus subtilis* isolated from cow dung microflora. *Agricultural Research* 1:273-279, doi:10.1007/s40003-012-0022-x.

Taalab, A.S., Ageeb, G.W., Siam, H.S. and Mahmoud, S.. 2019. Some characteristics of calcareous soils. A review. *Middle East Journal of Agriculture Research* 8:96-105.

Tian, J. 2021. Roles of phosphate-solubilizing microorganisms from managing soil phosphorus deficiency to mediating biogeochemical P cycle. *Biology* 10(2):1-19, doi:10.3390/biology10020158.

Turan, M., Gulluce, M., Vob Wirén, N. and Sahin, F. 2012. Yield promotion and phosphorus solubilization by plant growth – promoting rhizobacteria in extensive wheat production in Turkey. *Journal of Plant Nutrition and Soil Science* 175:818-826, doi:10.1002/jpln.201200054.

Wallace, B.C., Lajeunesse, M.J., Dietz, G., Dahabreh, I.J., Trikalinos, T.A., Schmid, C.H. and Gurevitch, J. 2017. OpenMEE : Intuitive, open-source software for meta-analysis in ecology and evolutionary biology. *Methods in Ecology and Evolution* 8:941-947, doi:10.1111/2041-210X.12708.

Wang, T., Liu, M. and Li, H. 2014. Inoculation of phosphate-solubilizing bacteria *Bacillus thuringiensis* B1 increases available phosphorus and growth of peanut in acidic soil. *Acta Agriculturae Scandinavica, Section B — Soil and Plant Science* October: 37-41, doi:10.1080/09064710.2014.905624.

Wang, Z., Xu, G., Ma, P., Lin, Y., Yang, X. and Cao, C. 2017. Isolation and characterization of a phosphorus-solubilizing bacterium from rhizosphere soils and its colonization of chinese cabbage (*Brassica campestris ssp. chinensis*). *Frontiers in Microbiology* 8(July):1-12, doi:10.3389/fmicb.2017.01270.

Wu, F., Hon, J., Wan, C., Wu, S. and Wong, M. 2012. Effects of earthworms and plant growth-promoting rhizobacteria (PGPR) on availability of nitrogen, phosphorus, and potassium in soil. *Journal of Plant Nutrition and Soil Science* 175(1995):423-433, doi:10.1002/jpln.201100022.

Xiao, C., Zhang, H. and Fang, Y. 2013. Evaluation for rock phosphate solubilization in fermentation and soil – plant system using a stress-tolerant phosphate-solubilizing *Aspergillus niger* WHAK1. *Applied Biochemistry and Biotechnology* 169:123-133, doi:10.1007/s12010-012-9967-2.

Xu, H. 2023. Combined phosphate-solubilizing microorganisms jointly promote *Pinus massoniana* growth by modulating rhizosphere environment and key biological pathways in seedlings. *Industrial Crops and Products* 191, doi:10.1016/j.indcrop.2022.116005.

Zheng, M.M., Wang, C., Li, W.X., Guo, L., Cai, Z.J., Wang, B.R., Chen, J. and Shen, R.F. 2021. Changes of acid and alkaline phosphatase activities in long-term chemical fertilization are driven by the similar soil properties and associated microbial community composition in acidic soil. *European Journal of Soil Biology* 104:103312, doi:10.1016/j.ejsobi.2021.103312.

Zúñiga-Silgado, D., Rivera-Leyva, J.C., Coleman, J.J., Sánchez-Reyez, A., Valencia-Díaz, S., Serrano, M., De-Bashan, L.E. and Folch-Mallol, J.L. 2020. Soil type affects organic acid production and phosphorus solubilization efficiency mediated by several native fungal strains from Mexico. *Microorganisms* 8(9):1-17, doi:10.3390/microorganisms8091337.