Research Article

Effect of Indigenous Phosphate-Solubilizing Bacteria on Phosphorus Availability and Shallot Productivity in Andisol

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Abstract | The high P fixation capacity of amorphous minerals in Andisol soils frequently restricts plant growth due to limited phosphorus (P) availability, an essential macronutrient. Utilizing native phosphate-solubilizing bacteria (PSB) from the shallot rhizosphere offers a promising strategy to enhance soil P availability and support sustainable plant growth. Assessing the impact of supplying native phosphate-solubilizing bacteria from the shallot rhizosphere on soil P availability and shallot growth in Andisol soil was the aim of this study. Two aspects made up the experimental treatments. The first factor was Andisol soil origin (Soil 1 and Soil 2). The second factor was type of phosphate solubilizing bacteria {Control, *Bacillus thuringiensis* (T11), *Bacillus cereus* (T21), *Bacillus cereus* (SE), *Bacillus cereus* (BJ12), *Burkholderia gladioli* (BJ22), *Bacillus cereus* (P21), *Bacillus cereus* (SP11), *Burkholderia gladioli* (SP12), and *Bacillus amyloliquefaciens* (SP21)}. The findings indicated that, in comparison to soil 2, Andisol soil 1 exhibits superior nutritional status and a greater capacity to sustain shallot development and yield. Using phosphate-solubilizing bacteria, specifically *Bacillus cereus* (SP11, SE, and T21), improved plant P absorption, soil P availability, and shallot productivity (71-76% than control). These results demonstrate PSB's potential as a sustainable approach to raise agricultural productivity and soil fertility in the results of this study confirm that the use of indigenous phosphate-solubilizing bacteria, specifically *Bacillus cereus*, is a strategic approach to optimizing phosphorus availability and shallot productivity in highland Andisols. This not only supports sustainable crop yield increases but also directly contributes to strengthening food security and efficient agricultural land management in Andisols.

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Introduction

A crucial macronutrient for plant growth and development, phosphorus (P) is particularly vital for photosynthesis, energy production (ATP), cell division, and the development of roots and tubers (Billah *et al*., 2019). Sufficient phosphorus availability is necessary for shallots (*Allium cepa* var.

aggregatum) to promote bulb formation and boost yields. However, soil P availability is often a limiting factor because most of it is in an insoluble form that limits plant uptake. A lack of phosphorus in the soil adversely affects root formation, vegetative growth, and fruit production, which eventually lowers agricultural yields (Jezek *et al*., 2023; Lopez *et al*., 2023); (Abobatta and Abd Alla, 2023).

The high phosphorus retention capacity in Andisols significantly reduces plant access to available P due to the content of reactive clay minerals such as allophane in the soil (Marpaung *et al*., 2021). The majority of phosphorus in soil is insoluble, thus even if it is abundant, its availability is poor. Retention by allophane can reach up to 97.8%, so that only about 0.1% of the total phosphorus can be absorbed by plants (Zhu *et al*., 2018).

An environmentally responsible and sustainable method to overcome phosphorus deficiency in agricultural soils is to use phosphate-solubilizing microorganisms (Kalayu, 2019; Tian *et al*., 2021). They mineralize organic phosphorus, solubilize inorganic phosphorus minerals, and store significant amounts of phosphorus in their biomass, these phosphate-solubilizing microorganisms (PSMs) form a diverse group of soil microflora that play a critical role in the soil P cycle (Gross *et al*., 2020; Liang *et al*., 2020). The processes of phosphate solubilization include the release of organic acids, phosphatase enzymes, lowering the pH of the soil, and boosting chelation activity, thereby improving P desorption and solubility. These microorganisms convert insoluble phosphorus into forms, such as orthophosphates, which can be readily taken up by plants (Billah *et al*., 2019).

Phosphate-solubilizing bacteria are among the many microorganisms that thrive in the plant rhizosphere (Hassan *et al*., 2020). Effective phosphate-solubilizing microorganisms include *Pseudomonas, Enterobacter, Bacillus* (Biswas *et al*., 2018), *Rhizobium*, *Arthrobacter*, *Burkholderia*, and *Rahnella aquatilis* HX2 (Liu *et al*., 2019; Zhang *et al*., 2019), as well as *Rhizobium*, *Arthrobacter*, and *Burkholderia*, (Perea Rojas *et al*., 2019).

Several studies have shown that the use of phosphate-solubilizing bacteria (PSB) can increase the amount of available phosphorus and crop yields in various agricultural systems. However, most studies using introduced PSB isolates have been conducted on non-volcanic soils or on major food crops such as maize and rice (Richardson *et al*., 2009; Alori *et al*., 2017). Studies on PSB in Andisol soils are usually limited to evaluating changes in soil P fractions, without linking them to soil fertility. Native phosphate-solubilizing bacteria are thought to have an advantage because they have evolved to local soil conditions such as soil chemistry, climate, and local microbial communities, making them more efficient than non-native microbes in increasing P availability and plant growth. This adaptation allows native microbes to colonize and survive better in the plant rhizosphere compared to introduced microbes (Sharma *et al*., 2013; Richardson and Simpson, 2011). Therefore, it is important to investigate and utilize native microorganisms in the shallot rhizosphere in Andisol soils to develop biofertilizers that can promote sustainable agriculture.

The objective of this study was to evaluate the effect of native phosphate-solubilizing bacteria isolated from the shallot rhizosphere to improve the soil P availability and shallot produvtivity in Andisol.

Materials and Methods

The study was carried out at Karo Regency's plastic house from January to June 2024. A factorial randomized block design was employed in this experiment. Two aspects made up the treatments under study. The first factor was Andisol soil origin (S1. Soil 1 and S2. Soil 2). The second factor was phosphate solubilizing bacteria {B0. Control, B1. *Bacillus thuringiensis* (T11), B2. *Bacillus cereus* (T21), B3. *Bacillus cereus* (SE), B4. *Burkholderia gladioli* (BJ22), B5. *Bacillus cereus* (P21), B6. *Bacillus cereus* (SP11), B7. *Burkholderia gladioli* (SP12), and B8. *Bacillus amyloliquefaciens* (SP21)}. Each treatment was replicated three times. The combination of each treatment is presented in Table 1.

Soil 1 comes from Dolat Rayat, Karo Regency and soil 2 comes from Siborong-borong, North Tapanuli Regency. Phosphate-solubilizing bacteria were isolated from the shallot rhizosphere by the USU and BRIN Agriculture faculties. The multiplication of isolates was carried out at the USU Laboratory. The bacterial inoculants were first grown on NA media and then incubated at 28°C for two to four days. For the therapy, each pure culture of phosphate-solubilizing bacteria was created until the bacterial population density approached 108 CFU ml-1.

Table 1: *The combination of each treatment*

Treatment Code	Soil origin	Phosphate-Solubilizing Bacteria
S1B0	Soil 1	Control (no bacteria)
S1B1	Soil 1	*Bacillus thuringiensis* (T11)
S1B2	Soil 1	*Bacillus cereus* (T21)
S1B3	Soil 1	*Bacillus cereus* (SE)
S1B4	Soil 1	*Burkholderia gladioli* (BJ22)
S1B5	Soil 1	*Bacillus cereus* (P21)
S1B6	Soil 1	*Bacillus cereus* (SP11)
S1B7	Soil 1	*Burkholderia gladioli* (SP12)
S1B8	Soil 1	*Bacillus amyloliquefaciens* (SP21)
S2B0	Soil 2	Control (no bacteria)
S2B1	Soil 2	*Bacillus thuringiensis* (T11)
S2B2	Soil 2	*Bacillus cereus* (T21)
S2B3	Soil 2	*Bacillus cereus* (SE)
S2B4	Soil 2	*Burkholderia gladioli* (BJ22)
S2B5	Soil 2	*Bacillus cereus* (P21)
S2B6	Soil 2	*Bacillus cereus* (SP11)
S2B7	Soil 2	*Burkholderia gladioli* (SP12)
S2B8	Soil 2	*Bacillus amyloliquefaciens* (SP21)

For each treatment, a 2:1 mixture of soil and chicken manure was utilized as the planting medium. First, the media is disinfected. Once it has cooled, it is placed in a 3 kg polybag and filled to the brim with sterile water. In a screen/plastic house, batu ijo variety shallot seeds are planted in polybags and treated with chemical fertilizer at rates of N 175 kg ha-1, P2O5 90 kg ha-1, and K2O 120 kg ha-1 at planting time and 1 month after planting.

One week after planting, two milliliters of phosphate-solubilizing microorganisms were applied to each plant, and five weeks later, 10 ml were applied (Sriwantoko et al., 2020) The inoculants were applied by watering directly into the planting hole in the morning.

Plants were maintained by watering every three to four days depending on climatic conditions, and by applying necessary pest and disease control measures. Seventy to eighty days after sowing, the plants were harvested. Plant height and stem diameter at 4, 6, and 8 weeks after planting, dry weight of plants and roots at 6 weeks post-planting, bacterial population, pH, C-organic, P available (Bray), P total (HCl 25%) in soil and P absorption by plant (multiplying the P content of the plant by the dry weight of the shoot), bulb weight per plant, bulb diameter, and yield were the variables of observation. The number of bacterial populations was observed by counting the colonies of phosphate-solubilizing bacterial that grew and the total population was calculated using the agar plate method (Plate Counting) (Richard, 2011), with the formula:

$$\text{Population (CFU ml} - 1) = \frac{a}{\text{bk}} \times \frac{1}{\text{df}}$$

Notes: CFU : Coloni Forming Unit
a : Average number of colonies per petri dish
df : Dilution factor
bk : dry weight of soil
The F test was used to examine the average data for each observation variable, and the HSD test was then performed at the 5% level.

Results and Discussion

Soil chemical properties before treatment

According to the soil's chemical characteristics prior to treatment, soil 1 had high levels of C-organic, N, and K2O, with respective contents of 4.91%, 52%, and 0.64 mg 100 g-1. The content of P2O5 (available P) was low at 2.36 ppm, while the content of P total (HCl 25%) and P retention was classified as high and very high, with value 54.45 mg100 g-1 and 152.2%. In soil 2, the soil's chemical characteristics are high C-organic content (4.37%), while N and K2O were moderate (0.48% and 0.40 mg 100 g-1, respectively). The content of P2O5 (available P) was also low at 2.21 ppm, while the content of P total (HCl 25%) and P retention was high and very high, with value 49.31 mg 100 g-1 and 103.9%. The pH in soil 1 and soil 2 is slightly acidic, and the pH of the planting medium in the polybags is acidic. Andisols in both locations exhibited a sandy-loam texture (Table 2).

Plant height and stem diameter increase

The soil origin treatment significantly affected the increase in plant height at 4 and 8 weeks after planting (WAP), while at 6 WAP, it significantly affected the interaction between soil origin and phosphate-solubilizing bacteria. In general, the soil 1 origin significantly produced greater plant height increase than the soil 2 origin at 4 and 8 WAP, with values of 5.70 cm compared to 4.51 cm and 23.43 cm

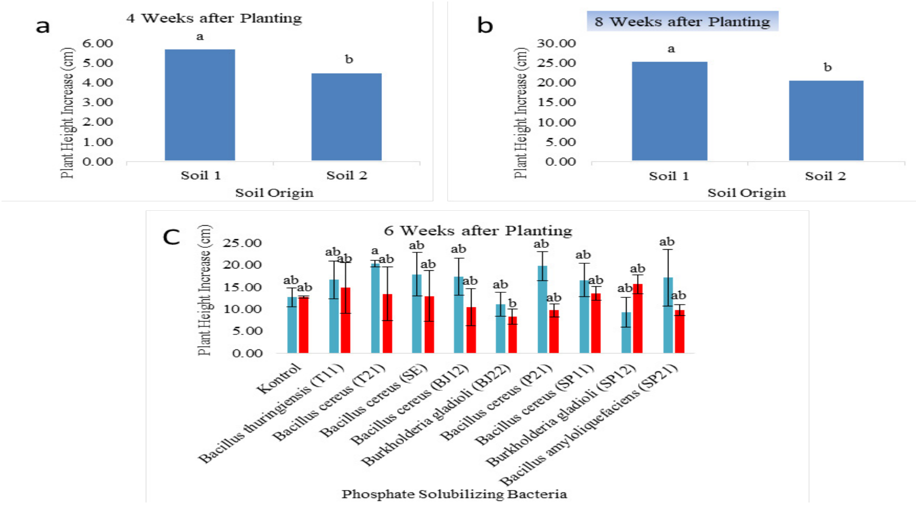

Figure 1: *Effect of phosphate solubilizing bacteria and soil origin on plant height increase at 4 (a), 6 (b) and 8 (c) WAP*

compared to 20.69 cm, respectively (Figure 1a, 1b). Six weeks after planting, the highest shallot plant growth occurred under the interaction of the soil 1 planting medium with the phosphate-solubilizing bacterium *Bacillus cereus* T21, recording 20.36 cm (Figure 1c) and significantly different from the other treatments.

Table 2: *Soil chemical properties before treatment*

Criteria	Soil 1		Soil 2	
	Value	Note*	Value	Note*
C-organic (%)	4.91	High	4.37	High
N (%)	0.52	High	0.48	Medium
K-dd (mg 100 g-1)	0.64	High	0.40	Medium
P2O5 – Bray 1 (ppm)	2.36	Low	2.21	Low
P2O5 HCl 25% (mg 100 g-1)	54.45	High	49.31	High
P-Retention (%)	97.80	Very high	93.90	Very high
Ca (mg 100 g-1)	18.14	High	5.91	Low
Fe (ppm)	38	High	37	High
Al-dd (cmol kg-1)	0.19	Very low	0	Very low
pH H2O	5.9	slightly acidic	5.88	slightly acidic
pH KCl	5	Acidic	5.5	Acidic
pH H2O (growing media)	4.67	Acidic	4.83	Acidic
C/N	9.44	Low	9.10	Low
Texture		Sandy Loam		Sandy loam
- Sand	83.04		88.68	
- silt	2.42		2.26	
- Clay	14.54		9.06	

The increase in stem diameter at 4, 6, and 8 WAP showed that the soil treatment had a significant effect, while the phosphate-solubilizing bacteria treatment had no significant effect. The soil 1 treatment resulted in a significantly higher increase in stem diameter than the soil 2, with values of 1.42 mm compared to 1.13 mm, 1.93 mm compared to 1.26 mm, and 2.12 mm compared to 1.42 mm, respectively (Figure 2).

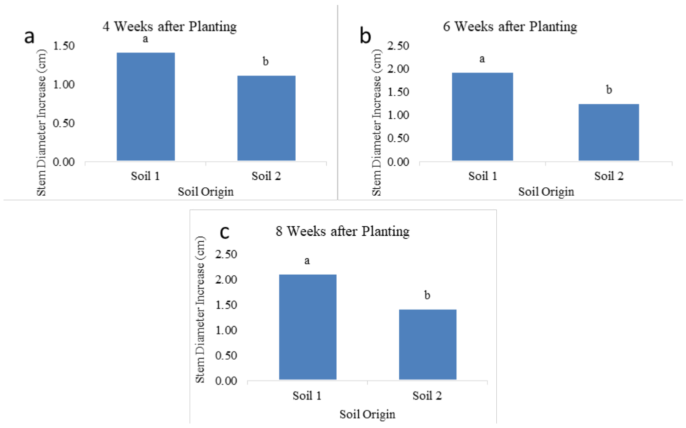

Figure 2: *Effect of soil origin on stem diameter increase at 4 (a), 6 (b) and 8 (c) WAP*

Plant and root dry weight

The soil origin treatment significantly affected plant dry weight and root dry weight, while the phosphate-solubilizing bacterial type treatment and the interaction between the two treatments did not significantly affect either variable. The dry weight of plants in the soil 1 medium was significantly higher than that in the soil 2 medium, recording 3.74 g compared to 2.17 g. Similarly, the dry weight of roots was also significantly higher in the soil 1 medium than in the soil 2 medium, with values of 0.31 g compared to 0.24 g (Figure 3).

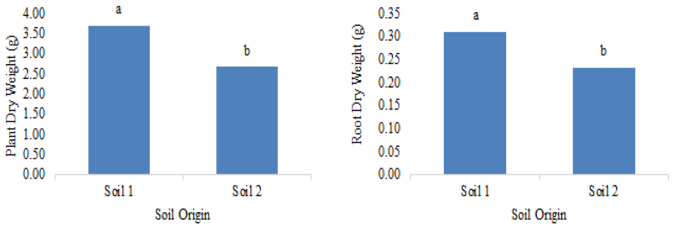

Figure 3: *Effect of soil origin on plant dry weight (a) and root dry weight (b)*

Bacteria population

The bacterial population results demonstrated that the type of phosphate-solubilizing bacteria and the soil origin treatment had a significant interaction. The highest bacterial population was obtained in soil originating from soil 2 with the administration of *Bacillus cereus* (SP11) bacteria, recording 7.86 x 108 CFU and did not differ significantly from *Bacillus thiringiensis* (T11), *Bacillus cereus* (T21), *Bacillus cereus* (BJ12), *Burkholderia gladioli* (SP12) bacteria from soil 1 and *Burkholderia gladioli* (SP12) bacteria from soil 2 (Figure 4). The lowest bacterial population was found in the treatment without the administration of phosphate-solubilizing bacteria in soil 1, with a value of 1.87 x 108 CFU g-1(Figure 4).

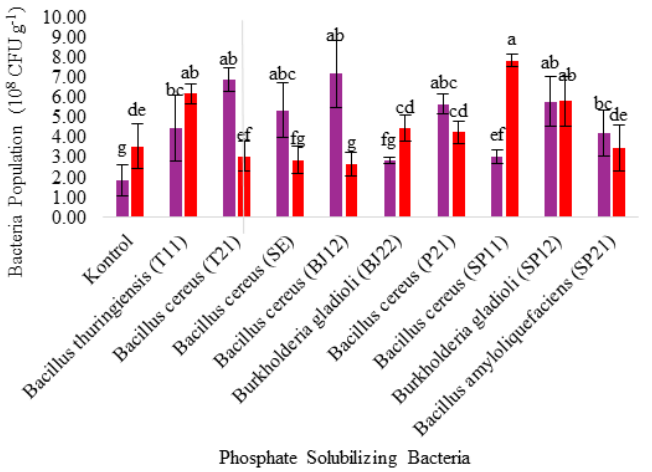

Figure 4: *Interaction of phosphate solubilizing bacteria with soil origin on bacteria population*

Soil chemical properties

pH (H2O), C-Organic, P-available (P Bray), P-total (25% HCl) and P-Retention

PH (H2O) and C-Organic

The soil's chemical characteristics demonstrate that the type of phosphate-solubilizing bacteria and the treatment of the soil's origin significantly affected on pH. The treatment of *Bacillus cereus* (T21) bacteria in the soil 1 medium produced the highest soil pH, recording 6.39, and did not differ significantly from other bacterial treatments but was significantly higher than the soil medium from soil 2, recording 5.77 (Figure 5a). The chemical properties of the soil Organic C were significantly affected by the soil origin treatment, while the type of phosphate-solubilizing bacteria had no significant effect. Organic C in the soil 1 origin was significantly higher than the soil 2 origin, with values of 7.15 compared to 5.79 (Figure 5b).

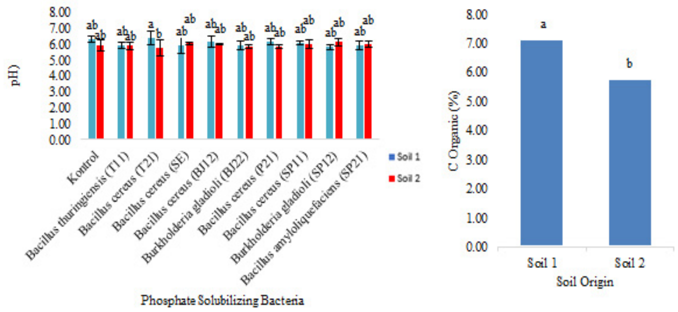

Figure 5: *Effect of phosphate solubilizing bacteria and soil origin on soil pH (a) and C-Organic (b)*

P-total, P-Retention and P-available

The interaction of soil origin treatment and phosphate-solubilizing microbial types significantly affected P-available (P Bray), P total (25% HCl) and P-Retention. The highest P total was obtained in the interaction of soil 1 origin treatment without the addition of phosphate-solubilizing bacteria, recording 1181.86 mg 100 g-1, while the lowest was in the interaction of soil 2 origin treatment with *Bacillus cereus* (SP11) and *Bacillus amyloliquefaciens* (SP21) bacteria, with value 662.66 mg 100 g-1; 738.46 mg 100 g-1 (Figure 6a).

The highest P retention of soil chemical properties was obtained in the interaction treatment of soil 1 origin without the addition of phosphate-solubilizing bacteria, recording 98.68% and the lowest was the interaction of soil 1 origin with the type of bacteria *Burkholderia gladioli* (BJ22), recording 79.88% and followed by the interaction of soil 2 origin with the type of bacteria *Bacillus cereus* (SP11), recording 84.49% (Figure 6b).

The interaction of soil 1 origin with the *Bacillus cereus* (SP11) bacteria produced the highest available P in the soil, with a value of 283.17 ppm and was not significantly different from the interaction of soil 2 origin with the phosphate-solubilizing bacteria *Bacillus cereus* (SE), which recorded 258.12 ppm (Figure 6c).

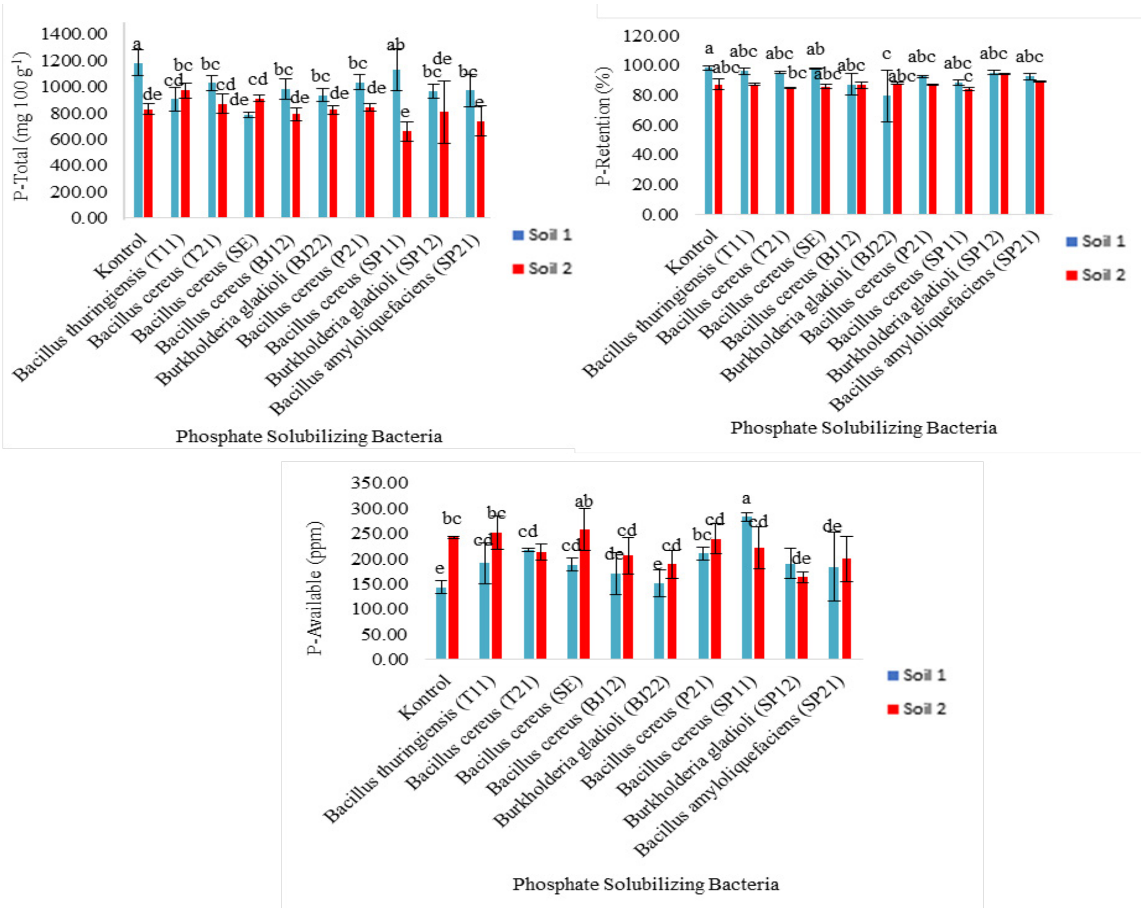

Figure 6: *Interaction of phosphate solubilizing bacteria with soil origin on soil P-total (a), P-retention (b) and P-available (c)*

Phosphate absorption

P uptake by plants showed that in the treatment of phosphate-solubilizing bacteria having a significant effect. In general, results indicated that the administration of phosphate-solubilizing bacteria resulted in higher P uptake than the control, except for the type of *Burkholderia gladioli* (SP12) which did not differ significantly from the control (1.09 mg plant-1 and 1.01 mg plant-1). The highest P uptake by plants was obtained by *Bacillus thuringiensis* (T11), recording 2.43 mg plant-1 and did not differ significantly from the remaining bacterial treatments (Figure 7).

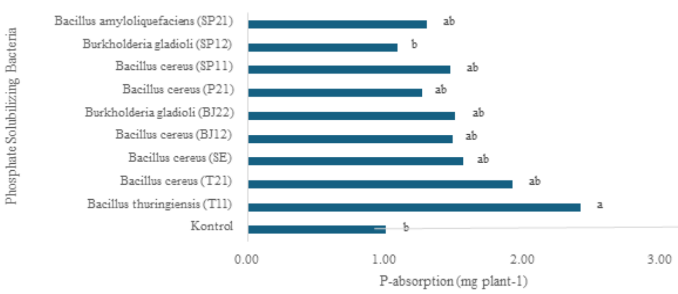

Figure 7: *Effect of phosphate solubilizing bacteria on P-absorption by plant*

Bulb weight per plant and bulb diameter

The results showed that all phosphate-solubilizing bacteria isolates were able to increase bulb weight per plant compared to the control. The highest bulb weight per plant occurred under *Bacillus cereus* treatments (SP11, SE, and T21), recording 20.80, 19.65, and 19.30 g plant^{-1}, respectively, which were all significantly higher than the control, 7.45 g plant-1 (Figure 8a).

Similarly, bulb diameter increased with the application of phosphate-solubilizing bacteria compared with the control. The highest bulb diameter was recorded under the *Bacillus cereus* (SP11) treatment, followed by *Bacillus cereus* (T2), *Burkholderia gladioli* (BJ22), *Bacillus thiringiensis* (T11), *Bacillus cereus* (BJ12) and *Bacillus cereus* (P21), recording 17.61 mm, 17.42 mm, 17.04 mm, 16.99 mm, 16.69 mm and 16.41 mm, respectively, and significantly different from the control, which was 12.87 mm (Figure 8b).

Yield per plot

The yield of shallots showed that the treatment of soil origin and type of phosphate-solubilizing bacteria had a significant effect. The soil 1 origin significantly increased the yield per plot compared to the soil 2 origin, recording 88.06 g compared to 60.77 g (Figure 9a). The administration of phosphate-solubilizing bacteria was able to increase the yield per plot compared to the control. The highest yield of shallots per plot was obtained in the *Bacillus cereus* (SP11) treatment, recording 108.97 g, followed by the *Bacillus cereus* (T21) and *Bacillus cereus* (SE) treatments, respectively, at 92.28 g and 91.23 g. The lowest yield of shallots per plot was obtained in the control treatment, recording 26.67 g (Figure 9b).

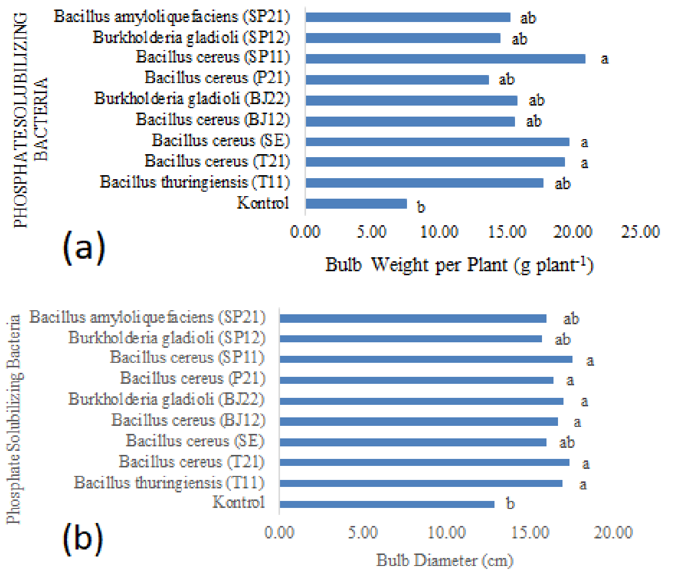

Figure 8: *Effect of phosphate solubilizing bacteria on weight per plant (a) and bulb diameter (b)*

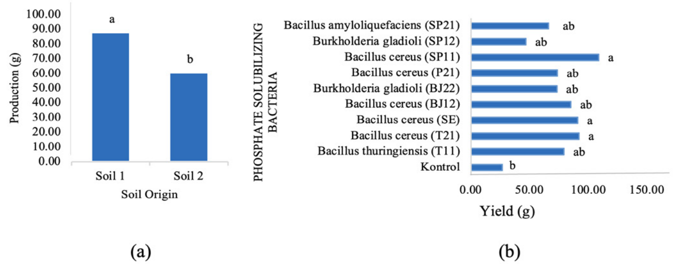

Figure 9: *Effect of soil origin (a) and phosphate solubilizing bacteria (b) on yield*

The research results showed that the soil chemical properties before treatment indicate key characteristics of Andisol soil, with high organic carbon content, acidic-slightly acidic pH, low P2O5 (available P), and high P retention. This trait is consistent with Andisol soils' characteristics, which include low P availability due to significant allophane phosphorus fixation (Zhu *et al*., 2018). According to (Nanzyo *et al*., 1993), the high to very high organic carbon contents observed, Andisol soils are likewise recognized for having a high organic carbon content. These characteristics make Andisol fertile but challenging for P management in agriculture. The pH values of the soil samples, which ranged from 5.45 to 6.56, were classified as slightly acidic. Most Andisol soils in Indonesia are acidic (pH 4.5 to 5.5), with a typical pH range of 3.4 to 6.7 (Sukarman and Dariah, 2015).

In general, soil 1 produced greater biomass accumulation and plant growth. This is believed to be caused by variations in the pretreatment chemical characteristics of the soil, with soil 2 providing moderate nutrient levels and soil 1 showing higher N, K_2O and C organic contents soil (Table 2). The use of phosphate-solubilizing bacteria also contributes to shallot growth, as PSB can provide the phosphorus nutrients needed for plant growth and development. Furthermore, PSB is categorized as a plant growth-promoting microorganism (PGPM), allowing it to produce growth hormones with phytostimulatory properties for plants. (Hassan, 2017; Compant *et al*., 2019). Plant development and yield are significantly enhanced by PGPMs that can solubilize phosphate (Tang *et al*., 2020; Fahad *et al*., 2015). For example, and *Bacillus* sp. CP h60 (Ditta *et al*., 2018) and *Bacillus* sp. STJP (Prakash and Arora, 2019) have been reported to produce the phytohormone indole-3-acetic acid (IAA). Additionally, *Bacillus* sp. and *Pseudomonas* sp. produce gibberellins (Setiawati *et al*., 2015) which are also linked to their phosphate-solubilizing abilities.

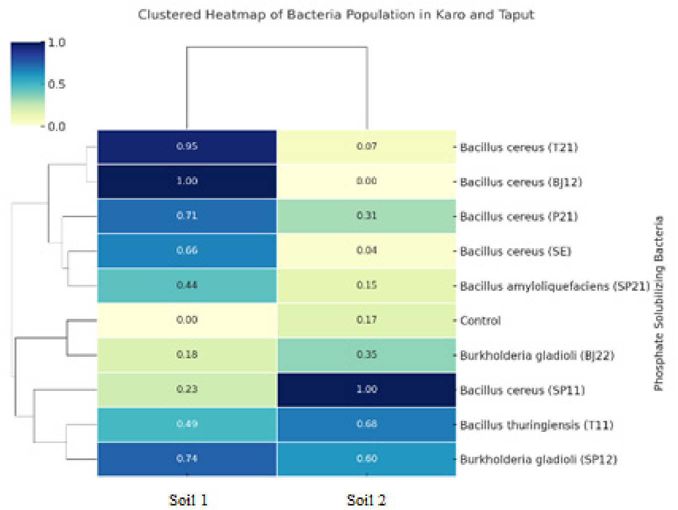

Figure 10: *Clustered heatmap of bacteria population on soil 1 and soil 2*

Bacterial populations are described through a clustered heatmap, where darker colors indicate higher bacterial populations (Figure 10). There is significant variation between treatments, both in soil 1 and soil 2. *Bacillus cereus* (T21) and *Bacillus cereus* (BJ12) showed high populations in soil 1 but low populations in soil 2, indicating these strains are more adaptive or competitive in soil 1 than in soil 2. *Bacillus cereus* (SP11) stood out with high populations in soil 2 but low populations in soil 1, indicating this strain is more suited or able to thrive in soil 2. *Burkholderia gladioli* (SP12) and *Bacillus thuringiensis* (T11) had relatively balanced populations in soil 1 and soil 2, suggesting these strains may be more stable in both locations. *Bacillus amyloliquefaciens* (SP21) and *Burkholderia gladioli* (BJ22) were in the cluster with lower populations than certain *Bacillus cereus* strains. The control had the lowest values, especially in soil 1. This confirms that treatment with phosphate solubilizing bacteria does increase the population compared to the control.

The activity of phosphate-solubilizing bacteria is strongly influenced by soil pH and P retention capacity. The highest activity occurs in soils with moderately acidic pH and high P retention, where phosphate-solubilizing bacteria play a crucial role in dissolving phosphorus fixed by Fe and Al oxides, thereby increasing P availability for plants. Soil acidity is a crucial factor in ensuring phosphorus immobilization in the soil (Zhu *et al*., 2018). Microbial growth and activity are significantly influenced by changes in the acidity of their environment. Bacteria generally have maximum solubility at pH 5.5-6. In acidic soils (pH <5.5), phosphorus is generally strongly adsorbed by aluminum (Al) and iron (Fe) oxides. This condition encourages phosphate-solubilizing bacteria to increase their metabolic activity through the production of organic acids capable of dissolving adsorbed phosphate. However, in very acidic conditions (pH <4.5), enzyme activity and phosphate-solubilizing bacteria growth can be inhibited, despite high P fixation rates. Conversely, at neutral pH, P binding by Al and Fe weakens, increasing P availability and decreasing the biological need for P solubilization, which reduces the activity of PSB. Soils with high P-retaining capacities, such as Andisols, which are rich in amorphous minerals (allophane and imogolite), have a high phosphate-binding capacity, resulting in very low available P despite high total P. This creates strong selection pressure for PSB to thrive and function actively. According to Kalayu, 2019, PSB is more active in soils with high fixed P. This also explains the generally higher population of PSB in soil 1 than in soil 2, as soil 1 has higher retention P and organic C content and a slightly acidic pH.

The pH and organic carbon content of each soil type showed an increase following the application of phosphate-solubilizing bacteria. This is related to the addition of phosphate-solubilizing bacteria, which resulted in an increase in pH and organic carbon. Generally, the addition of phosphate-solubilizing bacteria increases pH and organic carbon.

The amount of P that plants absorb is closely related with the soil's overall P concentration. Excessive plant absorption of P will lower the soil's overall P content. Although it was able to enhance accessible P, the addition of the phosphate-solubilizing bacteria *B. cereus* (SP11) often led to lower P total and P retention than the control. *B. gladioli* (BJ22) and *B. cereus* (SE) came next. *Bacillus* and *Burkholderia* have also been found to be efficient phosphate solubilizers in earlier research (Biswas *et al*., 2018; Liu *et al*., 2019). When phosphate-solubilizing bacteria are present, bound P can be dissolved, increasing the amount of P that is accessible in comparison to the 99.17% soil before treatment. This demonstrates that by decreasing P retention in the soil, the presence of phosphate-solubilizing bacteria contributes significantly to making phosphorus (P) more soluble for plants. The synthesis of organic acids, phosphatase enzymes, and siderophores are the primary methods by which phosphate-solubilizing bacteria solubilize P. In order to increase the amount of P available to plants, phosphate-solubilizing bacteria generate organic acids like citric, oxalic, and malic acids that can dissolve inorganic phosphate that is attached to soil minerals. Phosphatase enzyme production Phosphatase enzymes, which are secreted by phosphate-solubilizing microorganisms, hydrolyze organic phosphate molecules into inorganic forms that plants may absorb. Siderophores are produced by various phosphate-solubilizing microorganisms chelate metal ions like Fe^{3+} and Al^{3+}, which typically bind phosphate in the soil. Phosphate is made more accessible to plants and P soil retention is reduced by binding these metal ions. By generating phosphatase enzymes and low-molecular-weight organic acids, many phosphate-solubilizing microorganisms can dissolve and mineralize insoluble phosphate (Zhu *et al*., 2018). In order for plants to absorb P components to satisfy their demands, a group of phosphate-solubilizing bacteria that can secrete organic acids can remove phosphate from an insoluble form into an accessible form (Campos *et al*., 2018). Phosphate-solubilizing bacteria may be able to raise the amount of P in the soil (Hartati et al., 2023). The relative surface charge of cells in Andisol soil will bond with the charge of soil clay minerals, decreasing the clay minerals' ability to adsorb phosphate (Herzberg and Elimelech, 2008). In addition, organic acid anions produced by phosphate-solubilizing bacteria can block soil adsorption sites (Borggaard *et al*., 2005).

Shallot yields are significantly influenced by the addition of phosphate-solubilizing bacteria, as indicated by higher yields than without the addition of phosphate-solubilizing bacteria. In general, *Bacillus cereus* (SP11, SE, and T21) are able to increase yields. This indicates that phosphate-solubilizing bacteria, particularly *Bacillus cereus*, play a crucial role in increasing soil phosphate availability, thus supporting yield increases. The primary mechanism of phosphate-solubilizing bacteria is through the production of organic acids that lower the microenvironmental pH and release P ions from their bound form (insoluble phosphate) to become available to plants (Adhikari and Pandey, 2019). Organic acid release is the main mechanism by which microorganisms solubilize phosphate. Microorganisms can access labile inorganic phosphate (Pi) fixed in iron (Fe) or aluminium (Al) complexes by secreting organic acids, which chelate Fe and Al ions and release phosphorus (Baumann *et al*., 2018). *Bacillus* species produce organic acids, including lactic, propionic, acetic, and citric acids (do Carmo *et al*., 2019). Because it can create citric and gluconic acids and has an enzyme called phosphatase that aids in the mineralization of organic P, *Bacillus cereus* is regarded as one of the most effective phosphate-solubilizing bacteria (Satyaprakash *et al*., 2017). Phosphorus mineralization in soil is facilitated by enzymatic processes, such as the production of phosphatase and phytase (Billah *et al*., 2019).

Overall, phosphate-solubilizing bacteria significantly enhanced shallot growth and yield while improving soil chemical properties, particularly by increasing available P, reducing P retention, and slightly raising soil pH and organic carbon. These benefits were most evident in acidic Andisol soils with high P retention. Among the tested strains, *Bacillus cereus* SP11, SE, and T21 performed best due to their strong ability to solubilize phosphate bound by allophane minerals, Fe and Al through organic acid and phosphatase production, along with additional plant growth–promoting traits, resulting in improved soil P available and shallot productivity.

Conclusions and Recommendations

The study's findings indicate that while the chemical characteristics of the Andisol soils from soil 1 and soil 2 both have a high C-organic content, their high P-retention results in very low P availability. Compared to soil 2, the soil 1 has a higher N and K_2O concentration, which provides better nutritional support for plant growth. The continuously greater plant height, stem diameter, shoot dry weight, and root dry weight found in the soil 1 make this clear. The interaction between soil 1 and phosphate-solubilizing bacteria (PSB), particularly *Bacillus cereus* (SP11 and T21), was able to enhance plant growth, soil P availability, and soil pH compared to other treatments. In general, the application of PSB increased plant P uptake, bulb weight, bulb diameter, and shallot yield per plot compared to the control, with the best results obtained from *Bacillus cereus* (SP11, SE, and T21). *Bacillus cereus* (SP11, SE, and T21) can produce organic acids (citric acid, oxalic acid, and malic acid) that can dissolve inorganic phosphate bound to soil minerals in Andisol, also secrete phosphatase enzymes that hydrolyze organic phosphate compounds into inorganic forms and produce siderophores that chelate metal ions such as Fe^{3+} and Al^{3+}, which is proven effective by increasing soil available P and plant productivity. Future studies should focus on field-scale trials to ensure the consistency of PSB effectiveness under different agroecosystem conditions, as well as on the development of microbial consortia formulations for sustainable improvement of crop productivity.

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Novelty Statement

The novelty of this study lies in the utilization of local phosphate-solubilizing bacteria (PSB), particularly

Bacillus cereus (SP11, SE, and T21), in combination with Andisol soils from soil 1 and soil 2. The research demonstrates that the interaction between soil origin and PSB isolates significantly enhances soil phosphorus availability, plant P uptake, and shallot bulb yield. This provides new insights into managing Andisol soils with high P retention through a biological approach, offering a sustainable alternative to improve shallot productivity in the highlands of North Sumatra.

Author's Contribution

Agustina E. Marpaung: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing-original draft, Writing-review & editing, Visualization, Supervision and Funding acquisition.
T. Sabrina: Methodology, Validation, Formal analysis, Data curation, Writing-review & editing and Funding acquisition.
Abdul Rauf: Methodology, Validation, Formal analysis, Data curation, Writing-review & editing and Funding acquisition.
Dwi N. Susilowati: Methodology, Validation, Formal analysis, Data curation, Writing-review & editing and Funding acquisition.
All co-authors examined the final draft and provided their approval for the manuscript prior to submission.

Generative AI or AI assisted technology statement
During the preparation of this work, the author used Artificial Intelligence (AI). After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Conflict of interest
The authors indicate no conflict of interest in this work.

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