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The performance of *Bacillus pumilus* in boosting edamame yield is triggered by highly water-soluble phosphate fertiliser

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Abstract

The utilisation of biofertilisers in food crops has gained significant attention, as cultivation practices now focus not only on increasing productivity but also on promoting environmental sustainability. In this study, we evaluated the effectiveness of the phosphate-solubilising bacterium *Bacillus pumilus* (BP) in edamame cultivation using different types of phosphate (P) fertiliser: rock phosphate (RP) and superphosphate (SP-36). The bacterial strain isolated from the ebb-tide peatlands of South Kalimantan, Indonesia, was tested in a pot experiment conducted under 65.75 % shading, with both SP-36 and RP applied at 100 kg ha^{-1}. Our bacterial strain exhibited moderate phosphate solubilisation ability. The strain exhibited greater effectiveness when combined with SP-36, a highly water-soluble P fertiliser, rather than RP, both in enhancing edamame yield to a potential yield of 13.08 t ha^{-1} and in increasing available P in the growing media by 63.10 %. The primary yield contributing components were the number of pods (122.67) and seeds (275.67) per plant. A synergistic relationship between the number of nodules and yield improvement was observed in this treatment. Our strain enhanced nodule formation even in the absence of P fertiliser. Limited light intensity delayed flowering, which normally occurs 30 days after planting (DAP). However, the earliest flowering period was obtained when the bacterial strain was incorporated with SP-36 (39.67 days). The increase in yield associated with bacterial inoculation was accompanied by a slight increase in total chlorophyll content. In conclusion, BP has strong potential as an inoculant to optimise edamame yield, particularly when used in conjunction with a highly water-soluble P fertiliser. However, because this study was conducted under controlled pot and shaded conditions, further field-scale evaluation under different environmental conditions is required before these findings can be broadly applied.

Keywords: *Bacillus pumilus*; biofertiliser; edamame (*Glycine max*); phosphate-solubilising bacteria; rock phosphate

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1. Introduction

The demand for soybeans in Indonesia continues to rise as the population grows, driven by their versatility in various processed products such as soy sauce, tempeh, tofu and soy milk (1). However, a significant gap exists between soybean consumption and domestic production in Indonesia. In 2022, total domestic production was 241434.18 metric tons, whereas demand reached 1303605.31 metric tons, resulting in a substantial deficit of 81.48 % (2). On the other hand, productivity across Indonesian provinces from 2010–22 showed almost no significant increase. It remained relatively stable at 1.50–1.62 t ha^{-1} (2, 3), while edamame was approximately 3.5 t ha^{-1} (3). A significant supply shortage would leave the Indonesian government with no choice but to implement an import policy. This situation is typically influenced by the agricultural sector's contribution to a country's gross domestic product (GDP) (4). Therefore, increasing sustainable soybean production remains a critical issue in Indonesia.

Phosphorus is an essential nutrient for soybean growth, promoting root development, improving yield and seed quality and enhancing nodule nitrogen (N) fixation (5, 6). Indonesian farmers commonly use two types of phosphate (P) fertilisers, rock phosphate (RP) and superphosphate (SP-36) (7). Rock phosphate is derived from sedimentary rocks with phosphorus pentoxide (P_2O_5) content up to 27 %. It provides phosphorus in a poorly soluble form and is primarily recognised as a slow-release fertiliser (8). Due to its low solubility, it is generally not recommended for direct application as a P source for crops (9). However, its residual effects can be beneficial for subsequent planting seasons (10). The SP-36 was chosen because it contains about 36 % P_2O_5 that is easily soluble, so phosphorus becomes available quickly and provides a stable plant response.

Conversely, the effectiveness of natural P depends on mineral reactivity, particle size, plant type and soil conditions and is usually most optimal in acidic soils (pH ≤ 5.5). Although natural phosphate offers residual effects and longer-term amelioration benefits, SP-36 is more suitable for short-term crops that require immediate phosphorus. Its use in this study is based on consistent solubility and daily content, rather than always being superior to natural P (7).

Studies on *Bacillus*-based biofertilisers, coupled with fertiliser applications, including P fertiliser, to enhance soybean yield have been well reported. Bacteria in the genus *Bacillus* are recognised as efficient P-solubilising microbes (8). Their activity can enhance P availability by accelerating the conversion of non-available inorganic P to its soluble form, thereby improving plant P uptake (11). Treatments containing *Bacillus haynesii*, *Bacillus circulans* and *Bacillus subtilis* with the addition of *Priestia aryabhattai* and *Priestia megaterium* applied to soybeans result in 3.7 t grain yield ha^{-1} (12). *Bacillus* strains significantly enhance grain weight when applied with 100 kg P_2O_5 ha^{-1}, although their effects on the number of pods per plant and grains per pod remain negligible (13).

Within the genus *Bacillus*, several species have shown promise as plant growth-promoting bacteria; however, the genetic basis of their beneficial effects remains poorly understood. This study employed comparative genomic analysis to investigate four maize rhizosphere strains, revealing key molecular distinctions in nutrient utilisation, phytohormone production, iron acquisition and stress tolerance that underscore their potential as bioinoculants for sustainable agricultural practices. The application of 10^7 colony-forming units (CFU) mL^{-1} bacterial spore solution to seeds in a plant box significantly improved the initial growth of rice (14). Soybean yield and quality improve when inoculated with arbuscular mycorrhizal fungi (15). Many research studies have assessed the potential of *Bacillus pumilus* (BP) to enhance plant growth. *Bacillus pumilus* is a bacterium that naturally colonises the potato rhizosphere and has been widely used since 1995 to enhance potato tuber yield (16). Several strains of BP have been reported to promote plant growth by producing phytohormones such as indole-3-acetic acid, solubilising P, producing siderophores, stimulating root development and improving nutrient uptake. *Bacillus pumilus* inoculation has also enhanced rice growth, yield and tolerance to salinity stress (17–20). In addition, BP can suppress fungal phytopathogens, including *Rhizoctonia solani*, *Fusarium oxysporum*, *Fusarium solani* and *Fusarium equiseti*, through antagonistic mechanisms such as antimicrobial metabolite and hydrolytic enzyme production and induced systemic resistance (21, 22). This study shows that applying Rice-husk biochar and BP TUAT-1 improve rice growth and nutrient uptake, but the effects vary by rice genotype, highlighting the importance of considering plant genetics before large-scale use (17). There are still a few studies exploring the use of *Bacillus* sp. in edamame, though several studies on fertiliser application to maximise yield have been conducted. The yield of edamame, without co-inoculation with BP, can be increased to around 6.8 –8.9 t ha^{-1} (18, 19). Applying 171.5 kg of SP-36 ha^{-1}, combined with a nano foliar application at a concentration of 0.45 % cattle bone ash, results in an average pod weight of 81.88 g $plant^{-1}$ (18). However, a higher result of 109.4 g $plant^{-1}$ is achieved when soybeans are co-inoculated with *B. subtilis* and incorporated with 75 % of the recommended P fertiliser dose (20).

Bacillus sp. exhibits different responses to RP fertiliser, depending on its P_2O_5 content. When applied to RP with 13 % P_2O_5, this results in a lower P solubilisation index (2.13) than RP with 28 % P_2O_5 (3.13) or 30 % P_2O_5 (2.93) (21). Given SP-36's higher P_2O_5 content than RP and the *Bacillus* sp. ability to solubilise P, their combined application could significantly enhance edamame yield. This paper presents a novel approach to exploring a strain of BP from Indonesia's tropical peatlands and to examining its ability to solubilise P when incorporated with two types of P fertilisers (SP-36 and RP), with the aim of maximising edamame yield. Limited information exists regarding the interaction between P-solubilising *B. pumilus* and phosphorus fertilisers with varying solubilities in edamame cultivation. SP-36 provides readily available phosphorus, while the release of phosphorus from RP is primarily dependent on microbial solubilisation. Consequently, we hypothesised that inoculation with *B. pumilus* would improve phosphorus availability, plant growth and edamame yield, with the extent of the response varying between SP-36 and RP.

2. Materials and Methods

Experimental details and treatments

Time and venue

This experiment was conducted at the screen house of the Faculty of Animal and Agricultural Sciences, Universitas Diponegoro, Semarang City, Indonesia. It lasted for about 10 months, from March 2024 to January 2025. The experimental site was located at 7°03′07.82604″ S latitude and 110°26′31.42932″ E longitude. The altitude was 183 m above sea level. The average annual rainfall at the study location is approximately 1500 mm. This study consisted of two separate experiments. In experiment 1, a study was conducted to identify phosphate-solubilising bacteria (PSB) isolated from tropical peat in 2023. They were then propagated in the laboratory and used as biofertilisers as the research material for experiment 2. Experiment 2 aimed to study the application of the identified PSB in soybean incorporated with two different types of P fertilisers, SP-36 and RP, in a pot experiment.

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Experiment 1: Identification of phosphate solubilising bacteria

Process of isolation and multiplication of the phosphate solubilising bacteria

Phosphate solubilising bacteria exploration was conducted in ebb-tide peatlands in South Kalimantan, Indonesia. Soil samples were isolated from the rhizosphere of a rambai tree (*Baccaurea* sp.). Microbial isolation was performed using nutrient agar (NA) medium at 20 g L^{-1}, supplemented with 8 g agar. A total of 10 g of the soil sample was diluted in 90 mL of sterile water and homogenised using a shaker for 30 min at 120 rpm. The isolation procedure involved serial dilution from 10^{-1}-10^{-7}. From the 10^{-1}, 10^{-3}, 10^{-5} and 10^{-7} dilutions, 0.1 mL aliquots were separately collected and spread onto NA medium to obtain well separated and countable colonies. Bacterial colonies that grew after 48 hr were purified by aseptically transferring each bacterial isolate using a loop. The purification technique involved streaking each bacterial colony onto a new NA plate. Pure isolates were stored in test tubes containing 6 mL of NA medium. Purified microbes were tested on Pikovskaya agar medium. The presence of the PSB was recognised by the presence of a clear zone that developed around the bacterial colonies. Pikovskaya (PVK) medium was prepared with the following composition per litre: glucose, 10 g; calcium phosphate [$Ca_3(PO_4)_2$], 5 g; ammonium sulphate [$(NH_4)_2SO_4$], 0.5 g; sodium chloride [NaCl], 0.2 g; magnesium sulphate [$MgSO_4$], 0.2 g; potassium chloride [KCl], 0.2 g; yeast extract, 0.5 g; manganese sulphate [$MnSO_4$], 0.002 g; and ferrous sulphate [$FeSO_4$], 0.002 g (22). Agar was added when solid medium was required.

The P dissolution index (DI) was calculated to assess the phosphate-solubilising ability (PSA) of bacteria. SI was calculated using the following formula, (22)

$$DI = \frac{Diameter\ of\ colony + Diameter\ of\ clear\ zone}{Diameter\ of\ colony}$$

The PSA is categorised into three groups: low (DI < 2), moderate (DI 2–4 mm) and high (DI > 4 mm). The bacteria's ability to solubilise P was determined using the DI calculation and PSA categories.

The PSB inoculum was prepared by transferring bacterial isolates from stock culture slants into 200 mL of potato dextrose broth (PDB). Although PDB is commonly used for fungi, its carbohydrate-rich composition provides an effective carbon source for bacterial growth and metabolic activity, thereby supporting both bacterial biomass and extracellular metabolite production. The mixture was then shaken in a shaker incubator for 48 hr. Plating was carried out to determine the bacterial cell density of the PSB to be inoculated. Colony density was determined by serial dilution: 0.1 mL from each dilution was plated on NA medium. Bacterial cell density (CFU mL^{-1}) was determined by plate counting, as described below.

$$Bacterial\ cell\ density = \frac{Number\ of\ colony}{Volume\ of\ the\ sample\ taken} \times Dilution\ factor$$

The bacterial density of the biofertilisers reported in our study was based on the minimum technical requirements for biological fertilisers set by previous researchers, which specified a minimum of >1 × 10^8 CFU g^{-1} (22). The PSB inoculum was then transferred to PDB. 200 mL of PDB medium was inoculated with 20 loops of PSB, collected from an aseptically pure bacterial culture. The bacteria were activated by shaking them for 48 hr. The PSB inoculum prepared in PDB media resulted in a bacterial density of 1.8 × 10^8 CFU mL^{-1}. The bacterial genera were identified based on their morphological characteristics.

Identification of bacterial morphology

Bacteria were identified using macroscopic and microscopic observations. Macroscopic observations were carried out by examining the colony colour, shape, edge shape, elevation and surface of the bacteria. Microscopic observation was performed under a microscope connected to the display (Olympus C X 21) to obtain a detailed visual representation of the object. The object was prepared on semi-permanent slides using the standard method used in the microbiology laboratory.

Identification of bacterial molecular DNA

DNA from the bacterial isolates was extracted and purified using a DNeasy Plant Mini Kit (Qiagen, Germany). Bacterial DNA amplification was performed on a Thermo Cycler polymerase chain reaction (PCR) machine using the universal 16S rRNA primer. The purified isolates were submitted to the International Center for Biodiversity and Biotechnology (ICBB) for molecular identification.

Electrophoresis and DNA visualisation

The amplified products were analysed on a 1 % agarose gel in 1× Tris(hydroxymethyl)aminomethane-boric acid-ethylenediaminetetraacetic acid [Tris-borate-EDTA (TBE)] buffer. Electrophoresis was set at 50 volts for 60 min. The agarose gel was immersed in ethidium bromide (EtBr) for 15 min, then in sterile water for 5 min. Electrophoresis results were visualised using a UV transilluminator and documented using a digital camera. DNA sequencing of the PCR products was performed by First-BASE Laboratories (Malaysia). The sequencing results were analysed using the multiple alignment program ClustalW with Bioedit 7.2.5 and nucleotide sequences published on the GenBank site were aligned using the basic local alignment search tool-nucleotides (BLAST-N) program on the National Center for Biotechnology Information (NCBI) website. ClustalX 2.1, a Windows interface for the ClustalW multiple-sequence alignment program was used to determine the homology values for each sample. A phylogenetic tree was constructed in Mega 7.0 using the neighbour-joining method with 1000 bootstrap replicates (23).

Experiment 2: Application of identified phosphate solubilising bacteria and phosphate fertilisers in soybean

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Microclimate inside the screen house

The screen house had a 50 mesh. Fluctuations in air temperature and relative humidity (RH) at 08.00 am, 12.00 and 16.00 pm were measured using a data logger (GM-1365 Benetech, China) during the experiment from November 2024–January 2025. The light intensity at 08.00, 10.00 pm, 12.00 and 16.00 pm, both inside and outside the screen house, was measured and compared to determine the shading level inside the screen house.

Planting media and their physicochemical properties

The planting media consisted of mineral soil and well composted animal manure with a composition ratio of 2 : 1. Prior to use as planting media, approximately 1 kg of soil and mixed media (soil + animal manure) were sampled separately to describe their chemical properties, such as pH, C-organic, N-total, K-potential, P-available, K_2O and P_2O_5. After the media were uniformly mixed, they were placed into a polybag measuring 30 cm in height and 30 cm in diameter. Each polybag weighed approximately 3 kg. Thereafter, the media were sterilised by placing them inside a drum and steaming for 8 hr.

Experimental design

The soybean variety used in this study was Dega 1. The plants were planted in polybags. One seed was used per polybag. The experiment was statistically conducted using a completely randomised design with two factors and 3 replications. The first factor was the application of PSB, with two levels: absence and presence. The other factor was P fertiliser, with three levels: no P fertiliser, P fertiliser from SP-36 (100 kg SP-36 ha^{-1}) and P fertiliser from RP (100 kg RP ha^{-1}). The RP fertiliser used in our study contained 27 % P_2O_5. We reduced the dose of P fertiliser to 100 kg ha^{-1} from the recommended dose (150 kg ha^{-1}), as described in a previous study to determine the effectiveness of PSB (24). The doses of SP-36 and RP were equivalent to 1.2 and 1.6 g per plant, respectively. The PSB applied consisted of 10 mL of PSB inoculum collected from PDB media with a bacterial density of 1.8×10^8.

Maintenance and harvest during the experiment

Urea was applied at a rate of 75 kg ha^{-1}, while KCl was applied at 100 kg ha^{-1}. A planting space of 40 × 30 cm, equivalent to 83333 plants ha^{-1}, was set to calculate the fertiliser requirements per plant, resulting in total doses of 0.9 g urea and 1.2 g KCl per plant. SP-36 and RP fertilisers were applied seven days before planting. Two-thirds of the urea and KCl doses were applied at planting, with the remaining one-third administered at 35 days after planting (DAP). Harvesting was conducted at 100 DAP, following the edamame harvest standard, when the pods were firm and still green.

Variables measured during growth and at harvest

Several variables related to shoot growth and yield components, as well as total chlorophyll, were measured at both stages.

The variables plant height, number of living leaves and stem diameter were measured at 7-day intervals from 14–35 DAP. Stem diameter was measured using a calliper at 5 cm above the soil surface. The days to flowering ranged from 35–60 DAP. The flowering period was recorded from the first flower's appearance after planting. The plant height, number of living leaves, stem diameter, total shoot biomass (stem and leaves), shoot dry matter percentage (stem and leaves), root nodule weight, total leaf chlorophyll and P content in harvested seeds were measured at 100 DAP. The yield components included the total number of pods and seeds per plant, the total pod and seed weight per plant and the average pod and seed weight. The dry weight of plant shoots was determined after oven-drying at 80 °C for 24 hr.

Changes of organic carbon and available phosphate on the media

To examine the effectiveness of PSB in solubilising P in the growing media, organic C and available P were measured across all treatments at 100 DAP. Organic C levels were compared with pre-treatment values, while available P was evaluated relative to the treatment without PSB and P fertiliser.

Analysis method

Soil chemical properties

pH was measured using the H_2O method (25). Organic carbon (C-Organic) was analysed using the Walkey and Black method. The sample was measured using a spectrophotometer at 561 nm. Total nitrogen (N-total) was analysed using the wet combustion method with sulphuric acid [H_2SO_4] (25), while P_2O_5 and K_2O were analysed using nitric acid [HNO_3] (26). The value of P was determined from a spectrophotometer reading at 889 nm.

Total chlorophyll

The chlorophyll content was calculated at 35 DAP using the method described by previous researchers (27). A total of 250 mg of a fresh leaf sample was ground in a mortar and added to 25 mL of 80 % acetone. The green-coloured solution was then filtered using Whatman 42 filter paper. A total of 3 mL of the solution was placed in a cuvette and spectrophotometric measurements were conducted at 663 nm (A663) and 645 nm (A645). Total chlorophyll concentration (mg g^{-1}) was measured using the formula.

$$Total\ \ chlorophyll = (202.2 \times A645) + (8.02 \times A663)\, x \frac{V}{(100 \times W)}$$

where,

A645 = Absorption value at wavelength of 645 nm.

A663 = Absorption value at wavelength of 663 nm.

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V = Volume of acetone used to dissolve chlorophyll (mL)

W = Fresh leaf biomass (g)

Statistical analysis

The data obtained in this study were analysed using factorial two-way analysis of variance (ANOVA) with Statistix version 9.1 to determine the main effects of PSB, P source and their interaction (PSB × P source). When significant effects were detected, treatment means were compared using the least significant difference (LSD) test at the 5 % significance level ($p < 0.05$).

3. Results

Identification of bacterial isolates

Purification in Pikovskaya medium yielded eight potential strains: 1-5-A-PSB, 1-1-B-PSB, 1-3-A-PSB, 2-3-G-PSB, 2-3-D-PSB, 1-3-F-PSB, 2-1-A-PSB and 1-3-B-PSB. From these 8 strains, isolate 1-3-B-PSB was selected because it exhibited the largest halozone around its colony. This isolate was then subjected to a quantitative PSA assay. The measurement of the PSA for isolate 1-3-B-PSB is presented in Fig. 1. Isolate 1-3-B-PSB had a colony diameter of 2 mm and a halozone diameter of 4 mm, resulting in a DI of 3. This result indicated a moderate PSA.

The laboratory test results in Fig. 1 indicated that the bacterial strain 1-3-B-PSB had a rod-shaped morphology (*Bacillus*) and belonged to the Gram-positive bacteria group. The morphological characteristics of strain 1-3-B-PSB included a milky white colour, a round shape, wavy colony edges and a raised elevation. Another notable characteristic was the presence of endospores, which served as a survival mechanism under stressful conditions. Bacteria with these traits belong to the genus *Bacillus*. Based on molecular and phylogenetic tests, our isolated PSB showed 99.34 % similarity to the *B. pumilus* strain BAP 11 (Fig. 2). The 16S rRNA sequence was 826 bp long and showed 99.34 % query coverage with its closest reference sequence in the NCBI GenBank database. The sequence has been submitted to GenBank under accession number OM039405.1.

Microclimate inside the screen house

Large differences in light intensity were observed between the outside and inside at several measurement periods. On average, light intensity outside the screen house was 135750 lux, whereas inside, it was only 51467 lux (Table 1). This contrast led to soybean cultivation at a 65.75 % shading level. The average air temperature fluctuated throughout the day, measuring approximately 30 °C at 08:00 am and 16:00 pm, with a peak of 36.87 °C at 12:00 pm (Fig. 3a). Relative humidity (RH) was the highest in the morning (78.79 %) but sharply declined at noon (55.21 %), before rising again to 69.86 % by 16:00 pm. As the rainy season commenced, air temperature gradually decreased, while RH steadily increased (Fig. 3b).

Physicochemical properties of planting media

The soil used as the growing media was predominantly sandy (61.67 %), with smaller proportions of silt (27.50 %) and clay (10.83 %) (Table 2). It contained 12.59 ppm of available P and 114.2 ppm of K-potential. The incorporation of approximately 33 % well-composted animal manure (by weight) did not alter the pH of the media (5.8–5.9), but it increased the contents of C-organic, N-total and available P by 85, 97 and around 100 % respectively, compared to untreated soil. The increased levels of these soil chemical properties did not significantly alter the media's C/N ratio (9.00) compared with untreated soil (9.55). The concentrations of K_2O and P_2O_5 were 16000 and 10700 ppm respectively.

Effect on shoot growth

Differences in plant height, leaf number and stem diameter among soybeans treated with and without BP became noticeable around 21–24 DAP (Fig. 3). While plant height showed minor variation between treatments, differences in the other two variables were more pronounced, particularly at 35 DAP. However, the application of BP combined with P fertiliser did not significantly affect soybean shoot growth, although shoot biomass in treatments with PSB was higher than in treatments without BP (Table 3). The average plant height, number of leaves and stem diameter ranged from 68.67–80.67 cm, 16.33–20.67 and 5.10–6.77 mm respectively.

Effects on flowering period, phosphate content in seeds and total chlorophyll

None of the tested treatments significantly affected flowering duration or total chlorophyll levels. However, combining BP with SP-36 accelerated flowering, with plants blooming one day earlier than the control and nine days earlier than treatments without BP and P fertiliser. Soybeans co-inoculated with BP exhibited higher total chlorophyll (2.45–2.49 mg g^{-1}) and P content in harvested seeds (2.47–2.80 mg g^{-1}) compared to those without PSB, which showed values of 2.01–2.40 and 2.10–2.39 mg g^{-1} respectively (see Table 4).

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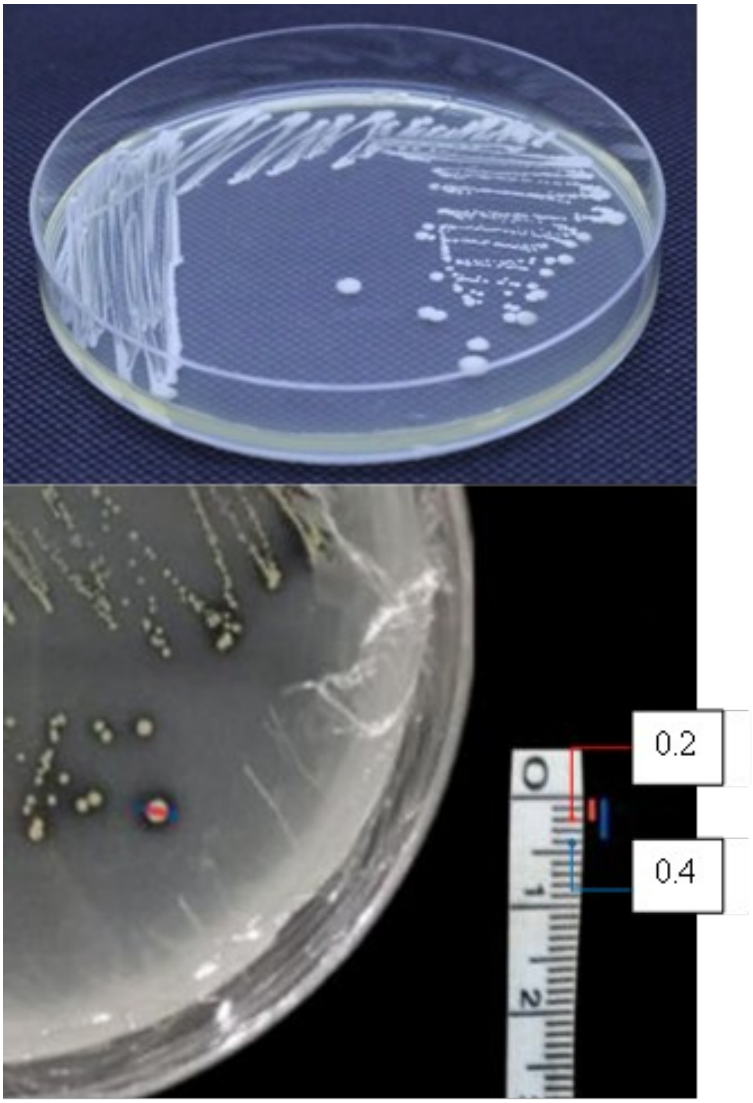


Fig. 1. A measurement of phosphate solubilising ability (PSA) on phosphate solubilising bacteria (PSB) isolate.

Effect on the yield component

The addition of SP-36 to BP-treated soybeans was more effective at increasing yield than the addition of RP fertiliser. This treatment significantly increased the number of pods and seeds per plant (Table 5) and boosted fresh seed biomass per plant by 90–119 %, 92–138 % and 117–149 % respectively, compared with the control (Fig. 4). Those yield components were not improved if P fertilisers were absent in the media. These results were clearly observed when compared with the treatment in which both PSB and P fertilisers were absent.

Effect on nodule formation

A synergistic increase in both yield and nodule number was observed in the treatment with BP and SP-36. It was not observed in the weight of nodules. BP itself was quite impressive in enhancing nodule formation. However, the increased yield in BP and RP treatments was not associated with nodulation. The number and weight of nodules were much lower than those in the treatment groups for BP and SP-36.

Changes of organic carbon and available phosphate in the media at 100 days after planting

Changes in C-organic and available P in the growing media from 0 to 100 DAP are presented in Table 6. Soil chemical properties increased across all treatments relative to pre-treatment levels, though the rate of increase varied among treatments (Table 6). The highest increase in C-organic was observed in soybeans treated with BP and SP-36. This treatment also resulted in the highest soil P availability (855.95 ppm), representing a 63 % increase over the treatment without BP and P fertiliser. In contrast, the combination of BP and RP showed a comparatively lower increase of only 18 % (623.86 ppm).

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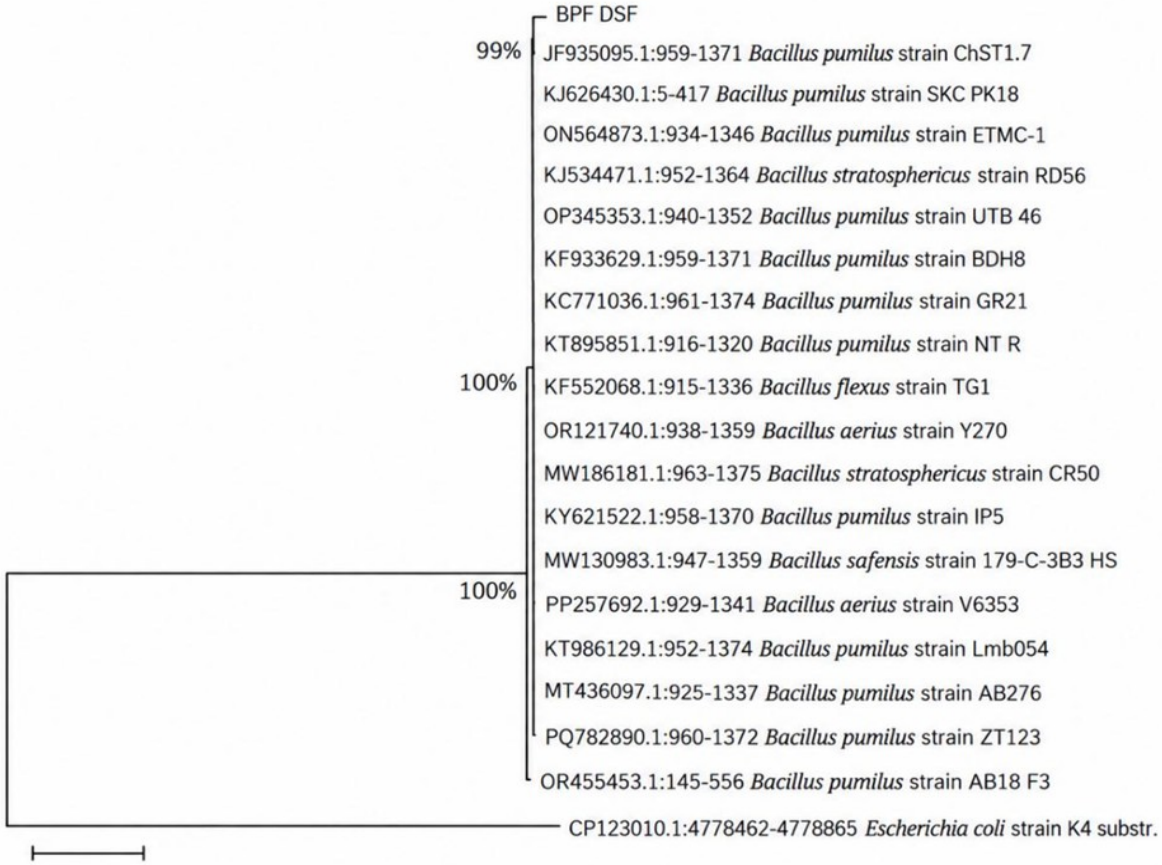


Fig. 2. A dendrogram of the *Bacillus* strain and the similarity of phosphate solubilising bacteria (PSB) isolate (red square) with another *Bacillus* species.

Table 1. Light intensity and shading level inside the screen house

Indonesian Time	Light intensity (lux)		Shading level inside screen house (%)
	Outside screen house	Inside screen house	
08.00 am	130000	35333	72.82
10.00 am	182000	74800	58.90
12.00 pm	198000	87667	55.72
16.00 pm	33000	8067	75.56
Mean	135750	51467	65.75

4. Discussion

The identified *Bacillus* bacteria showed a close similarity to the BP strain BAP 11. However, limited information is currently available regarding this strain. The ability of our BP strain to dissolve P was moderate, as indicated by the DI of 3. A higher solubilisation capability, with a DI of 6, has been previously reported for BP isolated from the potato rhizosphere. Phosphate-solubilising bacteria, *B. pseudomycoides*, may boost potato yields. The combination of chicken manure and *B. pseudomycoides* enhanced potato production by 33.79–56.24 %. It also increased the proportion of large tubers to 32.60–70.23 %, while reducing the share of small tubers to 43.61–72.32 %, compared to conditions without PSB. (28). *Bacillus pumilus* strain TUAT1 is a plant growth-promoting bacterium (PGPB) used as a biofertiliser containing its spores for rice (19).

In our study, the application of BP combined with SP-36 resulted in a potential edamame yield of 13.07 tons ha^{-1}, surpassing the yields, even under limited light intensity (18, 19).

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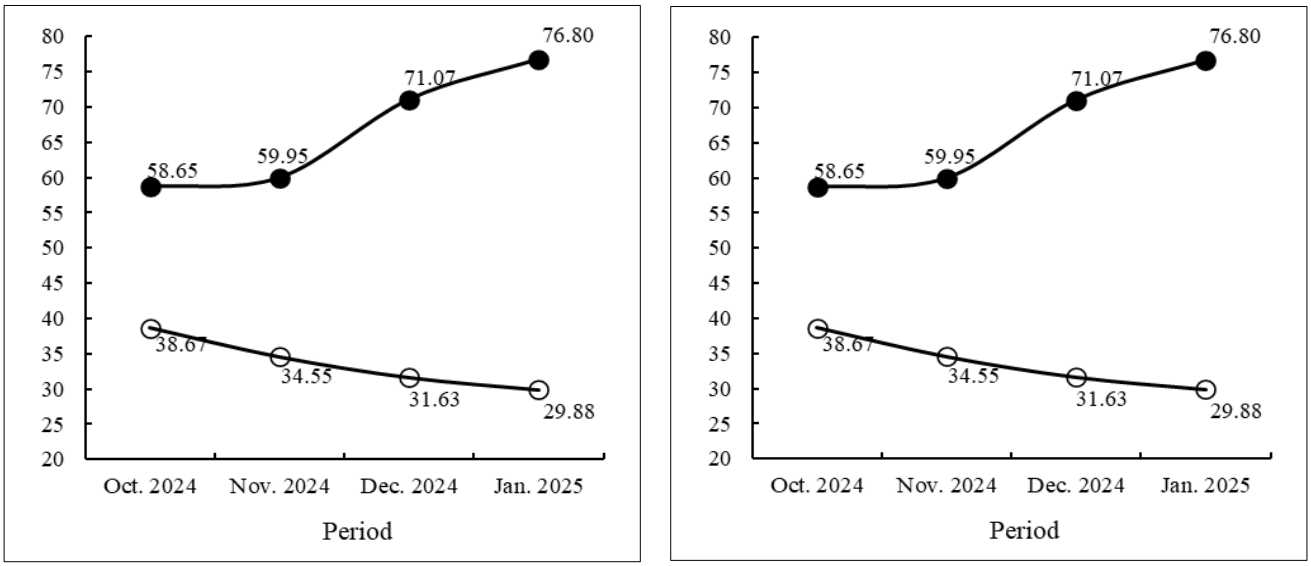


Fig. 3. Changes of means of air temperature and relative humidity inside the screen house. (a) day time, (b) during the period of experiment.

Table 2. Soil chemical and physical properties of the media

Soil properties	Soil	Soil + animal manure (2 : 1)
Chemical		
-pH	5.80	5.90
-C-organic (%)	3.63	6.75
-N-total (%)	0.38	0.75
-C/N	9.55	9.00
-Available P (ppm)	12.59	25.33
-P_2O_5 (ppm)		16000
-K-Potential (ppm)	114.20	
-K_2O (ppm)		10700
Physical		
-Silt (%)	27.50	
-Sand (%)	61.67	
-Clay (%)	10.83	

Composition ratio 2 : 1 based on the weight of the media. From total 3 kg media, it comprises 2 kg soil and 1 kg animal manure; C: carbon; N: nitrogen; P: phosphorus; K: potassium; P2O5: phosphorus pentoxide; K2O: potassium oxide.

Table 3. Effect on shoot growth

Treatment	Plant height (cm)	Number of total living leaves	Stem diameter (mm)	Fresh shoot biomass[1] (g)	Shoot dry matter[1] percentage (%)
	At 35 DAP			At 100 DAP	
No BP+No P fertiliser	68.67±12.58	16.33±4.93	5.10±1.13	102.27±34.10	25.19±12.43
No BP+100 kg SP-36 ha^{-1}*	80.67±10.12	19.00±3.46	5.60±0.69	106.70±24.33	21.83±2.98
No BP+100 kg RP ha^{-1}*	71.33±3.21	18.33±5.03	5.40±0.80	118.11±38.17	23.65±7.46
BP+No P fertiliser	71.33±4.93	19.67±2.08	5.83±0.95	138.11±3.71	19.27±0.49
BP+100 kg SP-36 ha^{-1}	73.67±3.21	20.67±4.04	6.77±0.25	135.71±26.00	22.65±7.20
BP+100 kg RP ha^{-1}	70.67±5.51	18.33±2.52	6.40±0.60	140.27±27.86	20.41±1.94
Significant	ns	ns	ns	ns	ns

*: control; ns: not significant; 1shoot biomass comprised of leaf and stem; DAP: days after planting. ±: standard deviation; BP: *Bacillus pumilus*.

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Table 4. Effect on flowering period, phosphate content in seed and total chlorophyll at 100 days after planting (DAP)

Treatment	Start of flowering (DAP)	P content in seed (mg g^{-1})	Total chlorophyll (mg g^{-1})
No BP+No P fertiliser	48.33±4.73	2.10±0.03	2.32±0.14
No BP+100 kg SP-36 ha^{-1}*	41.67±6.66	2.39±0.05	2.01±0.37
No BP+100 kg RP ha^{-1}*	41.00±1.73	2.31±0.03	2.40±0.40
BP+No P fertiliser	44.67±4.51	2.80±0.02	2.47±0.25
BP+100 kg SP-36 ha^{-1}	39.67±3.21	2.47±0.01	2.45±0.19
BP+100 kg RP ha^{-1}	45.67±9.02	2.60±0.04	2.49±0.21
Significant	ns	ns	ns

*: control; ns: not significant; DAP: days after planting. ±: standard deviation; BP: *Bacillus pumilus*.

Table 5. Effects on yield components

Treatment	Number of pods per plant	Number of seeds per plant	Number of seeds per pod	Average pod weight (g)	Average seed weight (g)
No BP+No P fertiliser	65.67±18.34 b	148.00±42.30 b	2.25±0.03 ab	1.19±0.02	0.19±0.01
No BP +100 kg SP-36 ha^{-1}*	64.33±14.01 b	143.67±35.47 b	2.23±0.11 ab	1.04±0.45	0.23±0.01
No BP +100 kg RP ha^{-1}*	56.00±4.00 b	116.00±11.27 b	2.07±0.10 bc	1.29±0.05	0.25±0.00
BP +No P fertiliser	67.67±4.73 b	135.33±9.29 b	2.00±0.05 c	1.20±0.05	0.23±0.03
BP +100 kg SP-36 ha^{-1}	122.67±25.72 a	275.67±58.40 a	2.25±0.01 ab	1.24±0.33	0.25±0.02
BP +100 kg RP ha^{-1}	72.33±28.92 b	167.67±49.90 b	2.38±0.23 a	1.56±0.08	0.28±0.07
Significant	s	s	s	ns	ns

*: control; ns: not significant; s: significant; means followed by the same alphabetical letters are not significantly different by the LSD test at 5 %; BP: *Bacillus pumilus*.

This yield is more than three times the average edamame productivity in Indonesia. Using BP as a biofertiliser, combined with P fertiliser from either SP-36 or RP, was more effective in enhancing yield components than the sole application of optimal fertiliser doses (29). The application of 10^7 colony-forming units (CFU) mL^{-1} bacterial spore solution to seeds in a plant box significantly improved the initial growth of rice (30).

These treatments resulted in a significantly higher number of pods per plant (72.33–122.67) and pod weight per plant (111.47–156.92 g), exceeding the previous results at 45.58 pods and 106.22 g of pods per plant, who recorded 104.9 g of pods per plant (19). The increased yield was primarily attributed to a higher number of pods per plant rather than the number of seeds per pod or the average seed weight (Table 6). Our findings align with those of early researchers, who studied co-inoculation with *Bacillus* strains and arbuscular mycorrhiza both in the presence and absence of P fertiliser (13). Since pod quantity directly influences the total seed quantity plant per plant, flower production and fruit set are essential components in determining soybean productivity (Fig. 5).

The ability of BP to solubilise P was enhanced by the addition of P fertiliser, particularly the highly water-soluble P fertiliser (Table 6).

Its effectiveness in transforming insoluble P into soluble P forms within a growth medium consisting of soil and well-composted animal manure into available P was 38.86 % higher than that of the treatment without PSB and P fertiliser at 100 DAP. When SP-36 was added, the available P increased by 63.10 %. These results may also have been influenced by seasonal factors, as the experiment was conducted during the rainy season. A previous study reported that SP-36 outperformed RP in enhancing maize productivity in Ultisol soils under wet conditions, whereas PR was more effective when combined with manure and applied in the dry season (7). The high concentration of available P in our media prior to treatment (25.33 ppm) might have effectively facilitated P transformation. In a no-tillage system, when soil P levels are naturally low (5.8 ppm), yield components show no significant response, even when co-inoculated with *B. subtilis* and *B. megaterium* supplemented with 150 kg P_2O_5 per ha from triple superphosphate (TSP) (31). Co-inoculation with BP integrated with SP-36 increased soil organic C content by 59 % relative to pre-treatment levels, achieving the greatest improvement among all tested treatments. According to a previous study, BP enhances nutrient availability by increasing soil organic C, T-nitrogen and extractable P (32). The beneficial effects of *B. pumilus* may involve several mechanisms beyond the direct solubilisation of inorganic P. The production of low-molecular-weight organic acids can decrease rhizosphere pH and chelate calcium (Ca), iron (Fe) or aluminium (Al) ions bound to P, thereby releasing P into forms that are more readily available for plant uptake. This mechanism is supported by early results (32).

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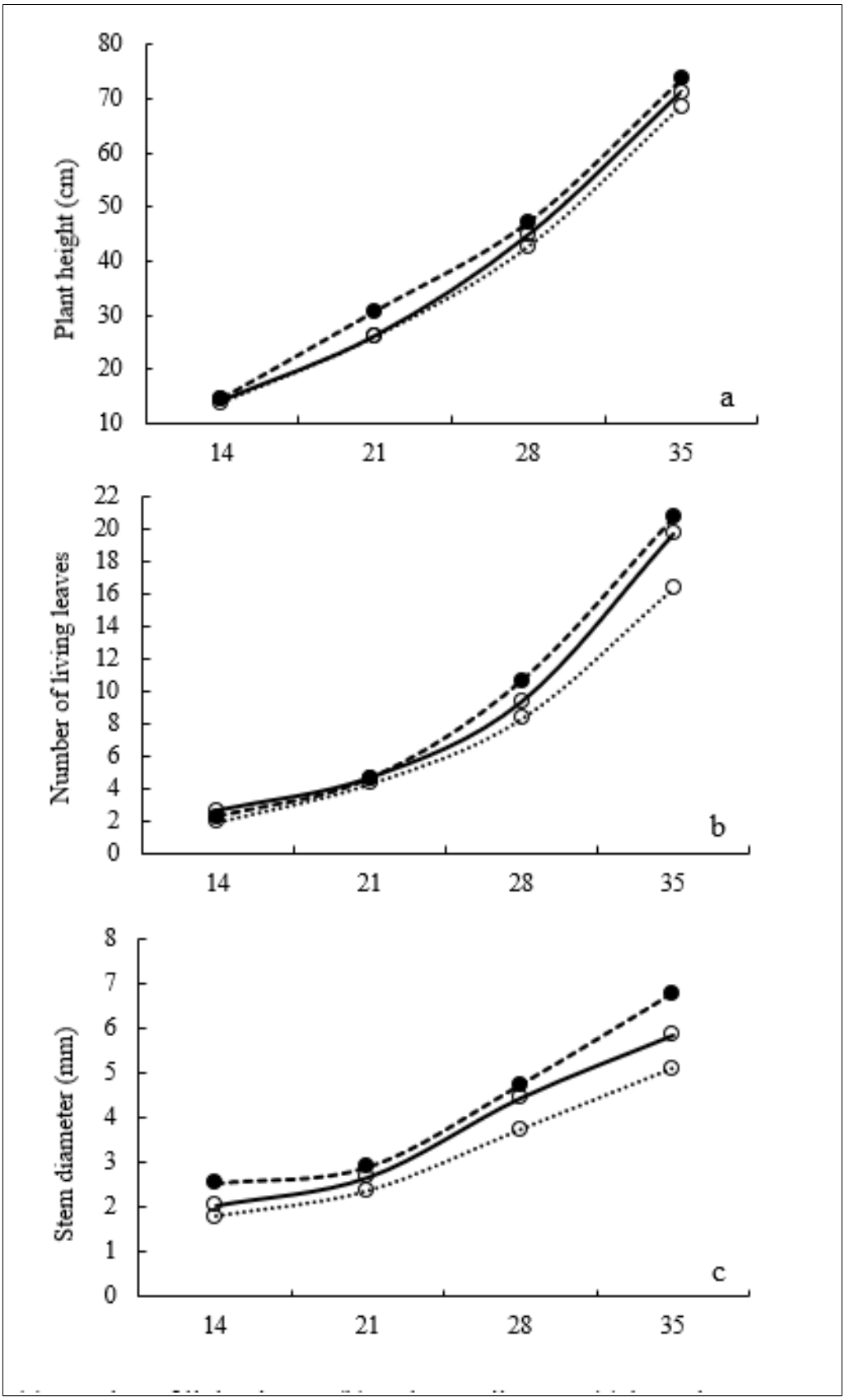


Fig. 4. Plant height (a), number of living leaves (b) and stem diameter (c) in soybeans treated with No BP+No P fertiliser, BP+No P fertiliser and BP+100 kg SP-36 ha^{-1}.

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Table 6. Changes of organic carbon and available phosphate (P) before and after treatments

Treatment	C-organic (%)	Available P (ppm)	Percentage of increase of avaiable P in the media[1] (%)
Before treatment (0 DAP)	6.75	25.33	
After treatment (100 DAP)			
No BP+No P fertiliser	7.58	524.79	0.00
No BP+100 kg SP-36 ha^{-1}*	8.31	738.97	40.63
No BP+100 kg RP ha^{-1}*	7.12	407.69	-
BP+No P fertiliser	7.53	727.69	38.66
BP+100 kg SP-36 ha^{-1}	10.75	855.95	63.10
BP+100 kg RP ha^{-1}	5.31	623.86	18.88
Significant			

DAP: days after planting; BA: biofertiliser application; SP: superphosphate; RP: rock phosphate; P: phosphate.

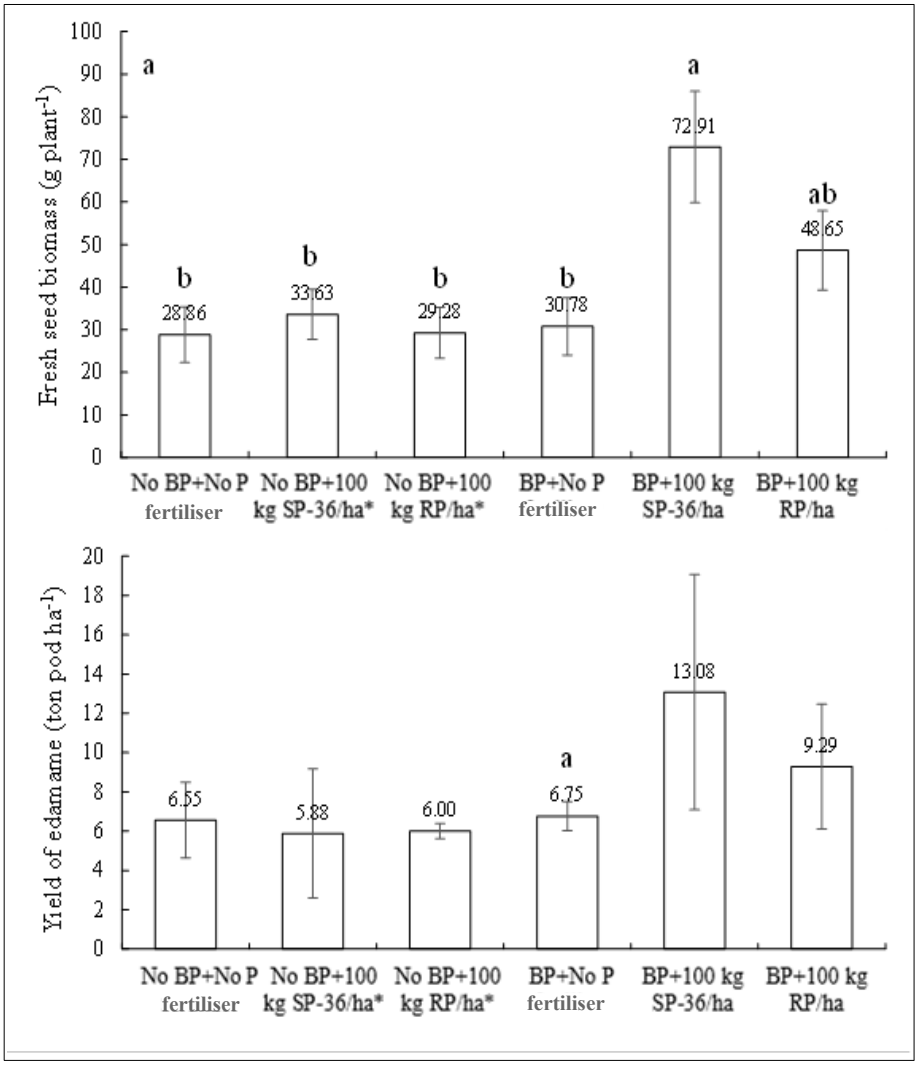


Fig. 5. Effect on fresh seed biomass per plant yield in ton pod ha^{-1}.

*: control; yield in ton pod ha^{-1} is calculated based on pod weight per plant and 83333 plant population ha^{-1} (planting space of 40 × 30 cm). Means followed by the same alphabetical letters are not significantly different by the LSD test at 5 %; ±: standard deviation; BP: *Bacillus pumilus.*

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The increased yield from BP co-inoculation was accompanied by a slight increase in total chlorophyll content, although the difference was not statistically significant (Table 5) or visually apparent (Fig. 6). The limited light intensity in the screen house may have contributed to this (33). The chlorophyll content and leaf colour index in soybean, measured with a SPAD meter, tended to decrease with increasing shading levels. However, the chlorophyll levels in BP-treated soybeans (2.47–2.49) in our present study at 35 DAP were almost comparable with those of 45-day-old soybeans cultivated in the field with 40 kg P_2O_5 ha^{-1} from single SP (2.36) (34). Approximately 65 % shade during cultivation delays flowering. Under normal conditions, our cultivar was expected to flower approximately 30 DAP. The shortest flowering period in our study was observed for the treatment co-inoculated with BP and SP-36 (39.67 DAP). The exceptionally late flowering period at 48.33 DAP observed in soybeans grown without BP and P fertiliser was associated with a higher percentage of shoot dry matter at 100 DAP. Different soybean cultivars exhibit distinct flowering timelines. For instance, the Ryokkoh cultivar begins to produce 50 % of its flowers at 30 DAP (19). Other studies have reported that certain local Indonesian cultivars flower within 35–40 DAP. The PGPB strains of *B. pumilus* have been described, including *B. pumilus* LZP02, *B. pumilus* JPVS11, *B. pumilus* TUAT-1, *B. pumilus* TRS-3 and *B. pumilus* EU927414 (35). These strains have been shown to produce a wide range of phytohormones and other plant growth-promoting substances. *Bacillus pumilus*, a resilient spore-forming bacterium within the Firmicutes, shows promise as a PGPB by producing phytohormones and enhancing plant traits, but further research is needed to understand its impact on native soil microbial communities and optimise its effectiveness in agriculture (35). *Bacillus pumilus* may also promote plant growth through the production of indole-3-acetic acid, which stimulates root elongation and branching and consequently increases the root surface area available for phosphorus and nutrient uptake. Siderophore production may further influence nutrient acquisition and suppress competing phytopathogens (35).

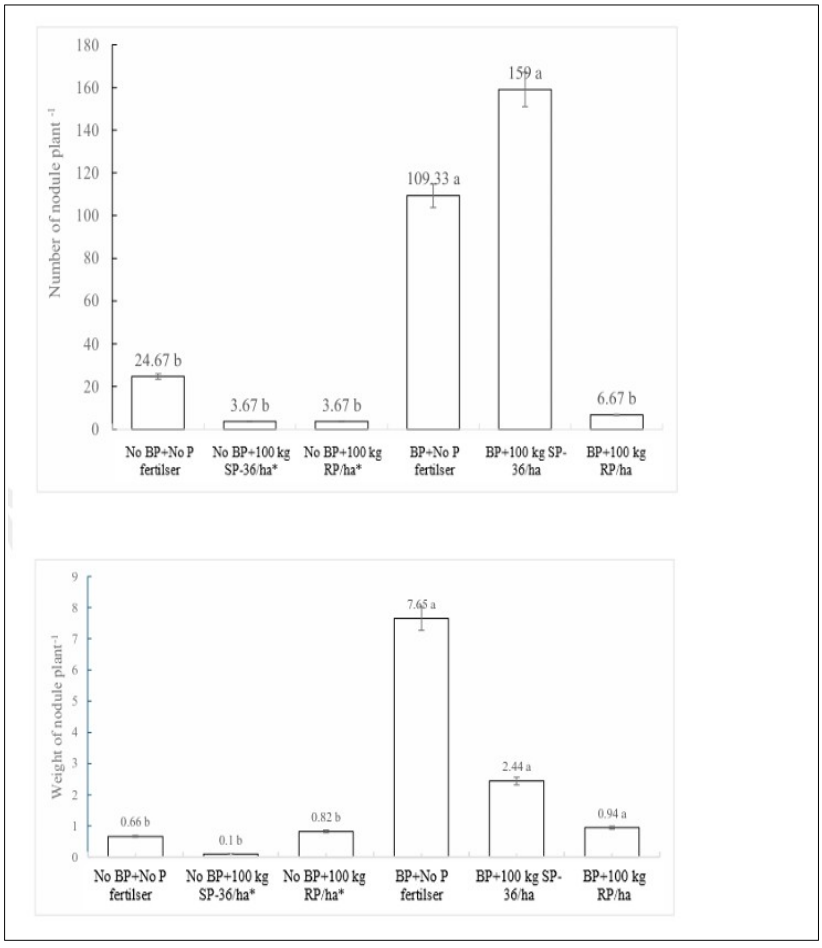


Fig. 6. Effect on nodule formation.

*: control; Means followed by the same alphabetical letters are not significantly different by the LSD test at 5 %; ±: standard deviation; BP: *Bacillus pumilus.*±: Standard deviation; BP: *Bacillus pumilus.*

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Nutrient availability, particularly P, is one of the most crucial factors influencing nodulation and efficiency of biological N fixation in soybeans (6, 36). Synergistic increases in soybean nodule formation and N fixation are consistently observed when acidic soils are limed to raise pH and P is supplied together with effective inoculant strains, such as *Bradyrhizobium* (37). However, when the soil pH approached alkalinity (7.58), nodule formation was inhibited, even when co-inoculated with saline resistant rhizobacteria and treated with 100 kg RP ha^{-1} (38). In our case, BP alone was effective in enhancing nodule formation, in both number and weight, even without the addition of P fertiliser. A synergistic increase in the number of nodules and soybean yield was observed when co-inoculated with BP and supplemented with highly water-soluble P fertiliser. However, it was not produced to its maximum when the RP was applied. This might have been due to insufficient P solubilisation from the RP fertiliser, as indicated by the concentration of available P in the media at 100 DAP. Compared with the treatment with BP and SP-36, the available P derived from RP, even with the addition of BP, was lower (18.88 %). No increase in available P was observed when RP was applied alone. Nevertheless, the number of nodules in our highest yield (159) was much higher than that in previous studies using various doses of *B. japonicum* supplemented with 100 or 200 kg P_2O_5 ha^{-1} (7–17) at 45 DAP (39) and with BP (30) at 35 days after emergence (40) (Fig. 7).

Soybean productivity issues require intensive research that relies not only on chemical fertilisers but also on the effective use of biofertilisers to maximise yield. Our findings highlight the crucial role of BP in optimising soybean yield, particularly when combined with a highly water-soluble P fertiliser. This potential is particularly evident in controlled environments. However, because co-inoculation studies tend to be more pronounced in pots than in field trials (40), it is essential to conduct field experiments on BP co-inoculation with highly water-soluble P fertiliser (41). Linking these findings to economic feasibility will provide valuable insights for practical agricultural applications. Nevertheless, organic acid production, phosphatase activity, phytohormone production and siderophore production were not directly quantified in the present study. Therefore, these mechanisms should be regarded as plausible explanations that require confirmation through further biochemical and molecular analyses.



B0R0: BP+No P fertiliser (SP-36)
B0R1: BP+100 kg/ha P fertiliser (SP-36)
B0R5: BP+100 kg/ha P fertiliser (RP)
B1R1: BP+100 kg/ha P fertiliser
B1R0: BP+No P fertiliser
B1R5: BP+100 kg/ha RP fertiliser (RP)

Fig. 7. Shoot performances of treated soybeans at 35 days after planting (DAP).

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5. Conclusion

Bacillus pumilus (BP) showed potential as a bioinoculant for improving soybean yield under the experimental conditions, although the identified strain exhibited a moderate phosphate (P)-solubilisation index. Its P-solubilising potential appeared to be more effective when combined with a highly water-soluble P fertiliser. This treatment significantly improved several yield-related traits, including the number of pods and seed biomass per plant and promoted earlier flowering.

These findings suggest that BP may contribute to improving soybean productivity in Indonesia. However, field validation across different environmental conditions and comprehensive economic feasibility studies are required before its large-scale application can be recommended.

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Authors' contributions

The DS conceptualised the study and wrote the manuscript. AFI was responsible for directing the study and advising on the manuscript's contents. FEP was responsible for conducting the study and analysing the data. FEP and EF corrected the grammar. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

References

1. Santhirasegaram V, George DS, Anthony KK, Singh HKB, Saruan NM, Razali Z, et al. Effects of soybean processing and packaging on the quality of commonly consumed local delicacy tempe. J Food Qual. 2016;39:675–84. https://doi.org/10.1111/jfq.12252
2. Harsono A, Harnowo D, Ginting E, Elisabeth DAA. Soybean in Indonesia: current status, challenges and opportunities to achieve self-sufficiency. In: Legumes Research - Volume 1. IntechOpen;2021. https://doi.org/10.5772/intechopen.101264
3. Rinady MVP, Nuraini Y, Prayogo C, Arfarita N. The effect of land management and organic matter inputs on bacterial population and soil nutrients across different types of agroforestry system. Biodiversitas. 2023;24(3):1333–45. https://doi.org/10.13057/biodiv/d240302
4. Pawlak K, Kołodziejczak M. The role of agriculture in ensuring food security in developing countries: considerations in the context of the problem of sustainable food production. Sustainability.2020;12(13):5488. https://doi.org/10.3390/su12135488
5. Taliman NA, Dong Q, Echigo K, Raboy V, Saneoka H. Effect of phosphorus fertilisation on the growth, photosynthesis, nitrogen fixation, mineral accumulation, seed yield and seed quality of a soybean low-phytate line. Plants (Basel). 2019;8(5):119. https://doi.org/10.3390/plants8050119
6. Zhu R, Yan W, Wang Y, Li Y, Zheng R, Dong W, et al. Plant growth-promoting rhizobacteria and Trichoderma shift common vetch (*Vicia sativa*) physiology and phyllosphere bacteria toward antagonism against anthracnose caused by Colletotrichum spinaciae. Grassl Res. 2024;3(3):275–89. https://doi.org/10.1002/glr2.12081
7. Husnain, Rochayati S, Sutriadi T, Nassir A, Sarwani M. Improvement of soil fertility and crop production through direct application of phosphate rock on maize in Indonesia. Procedia Eng. 2014;83:336–43. https://doi.org/10.1016/j.proeng.2014.09.025
8. Weeks JJ, Hettiarachchi GM. A review of the latest in phosphorus fertiliser technology: possibilities and pragmatism. J Environ Qual. 2019;48(5):1300–13. https://doi.org/10.2134/jeq2019.02.0067
9. Shen J, Yuan L, Zhang J, Li H, Bai Z, Chen X, et al. Phosphorus dynamics: from soil to plant. Plant Physiol. 2011;156(3):997–1005. https://doi.org/10.1104/pp.111.175232
10. Widiantini F, Hartati F. Endophytic bacteria origin of healthy rice plants produce antifungal volatile compound inhibited the growth of Pyricularia oryzae Cav., the causal agent of rice blast disease. Cropsaver. 2020;3(1):31–6. https://doi.org/10.24198/cropsaver.v3i1.28121
11. Anwar T, Qureshi H. Role of biocontrol agents in weed management – recent developments and trends. Acta Sci Pol Hortorum Cultus. 2022;21(6):155–62. https://doi.org/10.24326/asphc.2022.6.13
12. Marchão RL, Silva GC da andrade SRM de, Reis Junior FB dos, Barros Júnior MP de, Haphonsso RH, et al. Improving soybean development and grain yield by complementary inoculation with growth-promoting bacteria *Azospirillum, Pseudomonas*, *Priestia* and *Bacillus*. Plants (Basel). 2025;14(3):402. https://doi.org/10.3390/plants14030402
13. Leite RC, Pereira YC, Oliveira-Paiva CA, Moraes AJG, Silva GB. Increase in yield, leaf nutrient and profitability of soybean co-inoculated with Bacillus strains and arbuscular mycorrhizal fungi. Rev Bras Cienc Solo. 2022;46:e0220007. https://doi.org/10.36783/18069657rbcs20220007
14. Dushku E, Kotzamanidis C, Kargas A, Fanara-Lolou ME, Giantzi V, Krystallidou E, et al. Unveiling the genetic basis of biochemical pathways of plant growth promotion in *Bacillus pumilus* and the first genomic insights into *B. pseudomycoides* as a biostimulant. Curr Res Microbiol Sci. 2025;9:100419. https://doi.org/10.1016/j.crmicr.2025.100419
15. Seemakram W, Suebrasri T, Chankaew S, Boonlue S. Influence of arbuscular mycorrhizal fungi on soybean growth and yield: a metabarcoding approach. Plants (Basel). 2026;15(1):131. https://doi.org/10.3390/plants15010131

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https://doi.org/10.14719/pst.16599

16. Khan S, Srivastava S, Karnwal A, Malik T. Streptomyces as a promising biological control agents for plant pathogens. Front Microbiol. 2023;14:1285543. https://doi.org/10.3389/fmicb.2023.1285543

17. Win KT, Oo AZ, Ohkama-Ohtsu N, Yokoyama T. Bacillus pumilus strain TUAT-1 and nitrogen application in nursery phase promote growth of rice plants under field conditions. Agronomy.2018;8(10):216. https://doi.org/10.3390/agronomy8100216

18. Maulidayanti S, Indradewa D, Hanudin E. Physiological response, growth and yield of edamame soybean (*Glycine max* L. Merr.) under foliar application of nano cattle bone ash in Entisol. Planta Trop. 2023;11(1):11–8. https://doi.org/10.18196/pt.v11i1.13628

19. Alfiyah F, Purnamawati H, Purwono, Susila AD. Potassium fertiliser application rates for fertigated edamame grown on low-K soils. J Trop Crop Sci. 2024;11(3):320–8. https://doi.org/10.29244/jtcs.11.03.320-328

20. Aldrighi M, Lima JD, Fernandes-Júnior PI, Ferreira EPB. Performance of soybeans inoculated with multifunctional microorganisms under water-deficit stress. Soil Sci Soc Am J. 2025;89:e70131. https://doi.org/10.1002/saj2.70131

21. Dagnogo M, Kouadio KT, Tienebo EO, Kouadia AMJ, Adja NA, Kouakou KPM, et al. Spatial distribution, prevalence and severity of fungal diseases affecting black pepper cultivation in Côte d'Ivoire. J Anim Plant Sci. 2024;34(6):1469–85. https://doi.org/10.36899/JAPS.2024.6.0825

22. El-Saadony MT, Saad AM, Soliman SM, Salem HM, Ahmed AI, Mahmood M, et al. Plant growth-promoting microorganisms as biocontrol agents of plant diseases: mechanisms, challenges and future perspectives. Front Plant Sci. 2022;13:923880. https://doi.org/10.3389/fpls.2022.923880

23. Safitri D, Wiyono S, Soekarno BPW, Achmad. Mode of action of the endophytic yeast *Rhodotorula mucilaginosa* in controlling basal stem rot caused by Phytophthora capsici. IOP Conf Ser Earth Environ Sci. 2021;667(1):012050. https://doi.org/10.1088/1755-1315/667/1/012050

24. De Hita D, Fuentes M, Zamarreño AM, Ruiz Y, Garcia-Mina JM. Culturable bacterial endophytes from sedimentary humic acid-treated plants. Front Plant Sci. 2020;11:837. https://doi.org/10.3389/fpls.2020.00837

25. Jeksen J, Zubair H, Ahmad A, Tenriawaru N. Exploring the role of indigenous arbuscular mycorrhizal fungi for sustainable soil bio-conservation from Napun Gete Reservoir, Sikka District, Indonesia. Asian J Agric. 2025;9(1):305–15. https://doi.org/10.13057/asianjagric/g090132

26. Jones JB Jr. Plant Nutrition and Soil Fertility Manual. 2nd ed. Boca Raton (FL): CRC Press; 2012.

27. Enrico L, Díaz S, Westoby M, Rice BL. Leaf mechanical resistance in plant trait databases: comparing the results of two common measurement methods. Ann Bot. 2016;117(1):209–14. https://doi.org/10.1093/aob/mcv149

28. Marpaung AE, Karo B, Barus S, Hutabarat RC, Tarigan R. Application of organic fertiliser and phosphate solubilising bacteria to increase the growth and yield of potatoes in Andisol. Kultivasi. 2022;21(3):261–9. https://doi.org/10.24198/kultivasi.v21i3.41485

29. Ahmed HFA, Elnaggar S, Abdel-Wahed GA, Taha RS, Ahmad A, Al-Selwey WA, et al. Induction of systemic resistance in *Hibiscus sabdariffa* Linn. to control root rot and wilt diseases using biotic and abiotic inducers. Biology (Basel). 2023;12(6):789. https://doi.org/10.3390/biology12060789

30. Islam MM, Agake SI, Ito T, Habibi S, Yasuda M, Yamada T, et al. Involvement of peptidoglycan receptor proteins in mediating the growth-promoting effects of *Bacillus pumilus* TUAT1 in Arabidopsis thaliana. Plant Cell Physiol. 2024;65(5):748–61. https://doi.org/10.1093/pcp/pcae016

31. Silvestrini GR, Rosa EJ da, Corrêa HC, Magro TD, Silvestre WP, Pauletti GF, et al. Potential use of phosphate-solubilising bacteria in soybean culture. AgriEngineering. 2023;5(3):1544–54. https://doi.org/10.3390/agriengineering5030095

32. Kanari E, Karhu K, Salonen AR, Lemola R, Soinne H, Barré P, et al. Sensitivity of soil organic carbon stabilisation indicators to 24 years of land-use change across soil depth. Geoderma.2025;463:117573. https://doi.org/10.1016/j.geoderma.2025.117573

33. Huynh KA, Jolánkai M, Kassai MK. Influence of light intensity and nutrient concentration on soybean (*Glycine max* (L.) Merr.) seedling growth. Agronomy. 2025;15(5):1037. https://doi.org/10.3390/agronomy15051037

34. Manoj, Sharma MK, Meena H, Yadav RK, Yadav VK, Ghasil BP, Danga S. Productivity, profitability and quality of soybean [*Glycine max* (L.) Merrill] influenced by phosphorus and sulphur fertilisation. Legume Res. 2025;48(7):1202–6. https://doi.org/10.18805/LR-5021

35. Dobrzyński J, Jakubowska Z, Kulkova I, Kowalczyk P, Kramkowski K. Biocontrol of fungal phytopathogens by *Bacillus pumilus*. Front Microbiol. 2023;14:1194606. https://doi.org/10.3389/fmicb.2023.1194606

36. Liu H, Wang Z, Xu W, Zeng J, Li L, Li S, et al. Bacillus pumilus LZP02 promotes rice root growth by improving carbohydrate metabolism and phenylpropanoid biosynthesis. Mol Plant Microbe Interact. 2020;33(10):1222–31. https://doi.org/10.1094/MPMI-04-20-0106-R

37. Kabiru MR, Buernor AB, Dahhani S, Hafidi M, Jibrin JM, Jemo M. Soybean yield variability and predictability from applied phosphorus sources and rhizobia inoculation in Northern Nigeria. Front Sustain Food Syst. 2024;8:1428466. https://doi.org/10.3389/fsufs.2024.1428466

38. Sadiq M, Rahim N, Iqbal MA, Alqahtani MD, Tahir MM, Majeed A, et al. Rhizobia inoculation supplemented with nitrogen fertilization enhances root nodulation, productivity, and nitrogen dynamics in soil and black gram (*Vigna mungo* (L.) Hepper). Land. 2023;12(7):1434.

39. Orzali L, Allagui MB, Chaves-Lopez C, Molina-Hernandez JB, Moumni M, Mezzalama M, et al. Basic substances and potential basic substances: key compounds for a sustainable management of seedborne pathogens. Horticulturae. 2023;9(11):1220. https://doi.org/10.3390/horticulturae9111220

40. Rios FA, Freitas S, Estrada KR, Contiero RL, Braga G, Braz P, Roman R, et al. Agronomic performance of soybean treated with *Bacillus amyloliquefaciens*. Afr J Microbiol Res. 2018;12(45):1020–7. https://doi.org/10.5897/AJMR2018.9006

41. Pan L, Cai B. Phosphate-solubilising bacteria: advances in their physiology, molecular mechanisms and microbial community effects. Microorganisms. 2023;11(12):2904. https://doi.org/10.3390/microorganisms11122904

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