Pertanika J. Trop. Agric. Sci. 49 (S3): 31 - 50 (2026)

PERTANIKA JOURNALS

TROPICAL AGRICULTURAL SCIENCE

Journal homepage: http://www.pertanika.upm.edu.my/

Biofertiliser Application of PGPR *Pseudomonas aeruginosa* AGKT1 Enhances Nitrogen, Phosphorus, and Potassium Availability in the Potting Mixture of Oil Palm Seedlings

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ABSTRACT

Concerns over environmental consequences and sustainability issues regarding the overuse of chemical fertilisers in the oil palm industry have prompted the search for a biofertiliser alternative. This study explores the efficacy of a novel biofertiliser formulation containing *Pseudomonas aeruginosa* AGKT1, alone and in combination with chemical fertiliser (NPK 15:15:15), on soil nutrient availability and microbial activity in potting mixtures used to raise oil palm seedlings (*Elaeis guineensis*). A randomised complete block design (RCBD) assessed eight treatments replicated thrice over four months. Results were analysed using one-way ANOVA and mean comparisons via the LSD test. Treatment T4 (100 mL biofertiliser alone) yielded the highest microbial population (8.91 log CFU/mL), total N (0.29%), total soil phosphorus (353 mg/kg), available P, and Zn, reflecting a strong capacity for nutrient solubilisation. Meanwhile, T7 (100 mL biofertiliser + 50% NPK) recorded the highest soil magnesium (40.55 mg/kg) and available phosphorus (34.86 mg/kg), alongside strong total N performance, identifying it as the most efficient integrated option. The results clearly demonstrate the potential of the newly formulated biofertiliser inoculated with *P. aeruginosa* AGKT1 in nutrient solubilisation when applied alone and combined with chemical fertiliser, establishing it as a sustainable supplement for chemical fertilisation in oil palm cultivation.

Keywords: Microbial population, nutrient availability, oil palm, *Pseudomonas aeruginosa AGKT1*, potting mixture

ARTICLE INFO

Article history:
Received: 09 July 2026
Accepted: 14 October 2026
Published: 20 November 2026

DOI: https://doi.org/10.47836/pjtas.49.S3.02

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e-ISSN: 2231-8542

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INTRODUCTION

Oil palm occupies a prominent position in the agricultural sector and has scientific importance, especially in the tropical regions of Southeast Asia, Africa, and South America (Woittiez et al., 2017). This exceptional crop species is widely recognised for its many contributions to global agricultural and commercial sectors, as well as its significant role in scientific research aimed at enhancing our understanding of novel breeding techniques (Parveez et al., 2020; Qaim et al., 2020; Siddiqui et al., 2021). Malaysia has 5.87 million hectares of land under oil palm agriculture. In 2020, Malaysian export revenue increased (8.40%) to RM64.84 billion from the previous year (Mohamad et al., 2023). Biological control-based technology can be used as a good way to improve soil quality and increase its nutrient productivity, including essential nutrients needed for plant growth (Mahmud & Chong, 2021). Microbial biofertilisers represent a crucial facet of sustainable agriculture, achieving the dual goals of nutrient enrichment and disease suppression in soil (Duhan & Kataria, 2022). Enhanced soil nutrient pools, including organic carbon and a range of macro- and micronutrients, were observed under integrated application of microbial biofertiliser combined with reduced chemical fertiliser inputs, indicating an overall improvement in soil fertility status (Roslan et al., 2025). Additionally, this practice has proven to enhance the absorption of nutrients by the oil palm seedlings and improve the overall nutrient status of the soil (Ajeng et al., 2020). The oil palm seedlings that were subjected to a treatment involving the combination of a consortium of microorganisms and 30% chemical fertiliser exhibited superior growth performance and nutrient content when compared to the control treatments (Keni et al., 2023).

Different microorganisms can solubilise distinct micronutrients. Bacteria such as *Pseudomonas* spp. comprise several strains that can employ various mechanisms to solubilise multiple micronutrients (Nadeem et al., 2016). In previous studies, the strain Pseudomonas aeruginosa AGKT1 was found to fulfil all the necessary criteria as a promising microorganism for preparing biofertiliser (Basu et al., 2021; Duhan & Kataria, 2022; Timmusk et al., 2017). This strain not only improves nutrient absorption through fixation and solubilisation, but also synthesises phytohormones and organic acids, which are beneficial for plant growth (Parvin et al., 2020). *Pseudomonas* spp. is one of the widely studied plant growth-promoting rhizobacteria which enhance the availability of important soil nutrients required for plants (N, P, K, Zn, Fe) and improve plant uptake (Nadeem et al., 2016). The consortium inoculation of *Bradyrhizobium* + *Pseudomonas* demonstrated that it boosted soil mineral N and P, thereby enhancing uptake of N and P and yield of mungbean (& Sani, 2024). This particular microbial strain, named "*P. aeruginosa* strain AGKT1" a rhizobacterium developed at Universiti Putra Malaysia as the active component of a patented biofertiliser formulation that may be applied in combination with NPK fertiliser (Raja Abd. Rahman et al., 2014). It is stated that this strain can be applied alone or in

consortium as a biofertiliser to reduce chemical fertiliser inputs through its characteristic nutrient-solubilising and plant growth-promoting mechanisms.

Pseudomonas mendocina/putida have been shown to facilitate more uptake of K, Ca, Mg, and Zn nutrients by wheat shoots and improve the K^+/Na^+ ratio and yield under salt stress (Dasila et al., 2023). *Pseudomonas spp. such as Pseudomonas fragi* EPS1 and *Pseudomonas aeruginosa* (ZSB-22) solubilise the complex form of zinc in soil (Kamran et al., 2017). In addition, *Fluorescent pseudomonads* mobilise Zn and K in Zn- and K-deficient soils, thereby increasing their concentrations in rice tissues and biomass (Ullah et al., 2022).

Reported results have proven that *Pseudomonas* spp. could fix N, solubilise P and K, produce siderophores, and mobilise micronutrients, thereby increasing macro- and micronutrient availability in the rhizosphere and supporting plant nutrition and soil health (Sah et al., 2021). While studies on microbial-based biofertilisers have been conducted on oil palm seedlings, most have used multi-strain consortia and assessed seedling growth or tissue nutrient content (Ajeng et al., 2020; Amir et al., 2005; Keni et al., 2023; Zainuddin et al., 2022). Consequently, the precise impact of an individual strain on the nutrient status of the nursery growing medium remained largely unknown. Furthermore, there is a gap in studies on whether the effect of a single *Pseudomonas* inoculant could sustain or exceed the nutrient availability achieved by full-dose NPK when chemical fertiliser is reduced by 50%, yet this has not been examined.

In light of the environmental concerns arising from the excessive usage of chemical fertiliser in the oil palm sector, this integrated approach offers a sustainable choice by improving soil biological and chemical properties while reducing ecological degradation. The synergy between microbial activity and reduced chemical inputs promotes balanced nutrient supply and supports soil microbial health. Consequently, the application of *P. aeruginosa* AGKT1-based biofertiliser, combined with reduced chemical fertiliser, offers a promising strategy for sustainable oil palm cultivation while strengthening soil ecosystem resilience. Therefore, this study aimed to evaluate the integrated application of biofertiliser and reduced chemical fertiliser as a strategy to enhance the microbial activity and soil-available nutrients in the potting mixture of oil palm seedlings.

MATERIALS AND METHODS

Experimental Design and Nursery Preparation

The experiment on Dura × Pisifera oil palm seedlings (RISDA, Malaysia) was established in a glasshouse at Universiti Putra Malaysia using a randomized complete block design with three replications. Seedlings were cultivated in 15 kg polybags (35 × 38 cm) containing a mixture of sieved topsoil, compost, and sand at a ratio of 3:2:1. Seedlings received NPK 15:15:15 fertiliser (18 g per plant) (Adileksana et al., 2020) and stage-dependent irrigation (50-120 mL). Soil N and P were determined via Kjeldahl digestion and molybdenum blue

Table 1
Treatment details

Treatment	Description	Reference
T0	No chemical fertiliser and no biofertiliser (Control)	
T1	Normal fertiliser (NPK Green, 15:15:15) (100% = 18 g)	Nusaibah et al., 2017
T2	25 mL Biofertiliser	Ajeng et al., 2020; Zainuddin et al., 2019
T3	50 mL Biofertiliser	”
T4	100 mL Biofertiliser	”
T5	T2 + 50% NPK Green (50% = 9 g)	”
T6	T3 + 50% NPK Green (50% = 9 g)	”
T7	T4 + 50% NPK Green (50% = 9 g)	”

colorimetry, respectively, while K, Mg, B, and Zn concentrations were quantified using ICP-AES. Treatments (Table 1) were administered over a four-month period. Chemical fertilisers were applied at 15-day intervals. The biofertiliser inoculum (10^6 CFU/mL) was applied at 14-day intervals for biofertiliser-only treatments (T2-T4), whereas combined treatments (T5-T7) received the inoculum one week following each chemical fertiliser application.

Determination of Soil Nutrients

Soil samples were air-dried, homogenised, and sieved through a 2 mm mesh before analysis. Macronutrients were assessed after four months to account for mineralisation and seasonal variation. Total nitrogen (N) was measured using the Kjeldahl method. Briefly, 1 g of soil was digested with concentrated sulfuric acid in the presence of a catalyst to convert organic N to ammonium sulfate. After the digestion, it was distilled with NaOH, and the liberated ammonia was trapped in boric acid and titrated with 0.01 N HCl (Okalebo et al., 1993). Total phosphorus (P) was determined using the molybdenum blue colorimetric method (Murphy & Riley, 1962), in which 0.5 g of soil was digested with concentrated H_2SO_4 and H_2O_2 at 350 °C temperature, allowed to react with molybdenum blue reagent, and absorbance was measured at 882 nm against phosphate standards using a spectrophotometer (Hansen & Koroleff, 1999). Available P was extracted using the double acid method (0.05 M HCl + 0.025 M H_2SO_4) (Sharpley, 2009), with 20 mL extractant shaken at 180 rpm for 10 minutes, then filtered using Whatman No. 2 filter paper, and P was determined colorimetrically at 882 nm following the same procedure for total P. Total Mg, Zn, and B concentrations were determined by aqua regia digestion (HCl: HNO_3, 3:1) (& Stein, 1983), whereby 2 g of soil was refluxed for 30 minutes, filtered into a 50 mL volumetric flask, and elemental concentrations quantified by Atomic Absorption Spectrometry (Perkin Elmer Analyst 400 AAS) and expressed as mg/kg.

Determination of Microbial Population in Soil

To assess the microbial population in soil, 1 g of soil from each treatment was collected after 45 days and serially diluted following standard microbiological procedures (Hernández-Fernández et al., 2021; Timmusk et al., 2017). The soil sample was initially mixed with 100 mL of distilled water, and a 10-fold serial dilution was performed up to 10^{-8}, using 1 mL aliquots transferred into 9 mL sterile distilled water (Naureen et al., 2015). Dilutions 10^{-4}, 10^{-6}, and 10^{-8} were plated on nutrient agar to determine colony-forming units (CFU) (Khan et al., 2018). For this study, the 10^{-6} dilution was selected to quantify the bacterial population and used in further analysis.

Statistical Analysis

Statistical analysis was performed using one-way ANOVA (SPSS v. 17.0), and mean comparison was done using the Least Significant Difference (LSD) test ($p < 0.05$).

RESULTS AND DISCUSSION

Effect of Biofertiliser on Microbial Population in the Potting Mixture of Oil Palm Seedlings

The presence of microorganisms in soil plays a critical role in enhancing micronutrient availability in crops through mechanisms such as siderophore production, secretion of organic acids, and release of phenolic compounds (Singh et al., 2021). The presence of endophytic bacteria, exemplified by *Pseudomonas* spp., showed the remarkable capacity to establish rhizo-competence, engage in antibiosis, induce resistance, and foster plant growth within the rhizosphere region (Nusaibah et al., 2017). However, in this experiment, soil microbial populations were monitored at four intervals using a dilution factor of 10^{-6}, and the results are presented in Table 2. The minimum values were seen in the T0 and T1 treatments at the end of the experiment, when a combination of NPK and a newly developed biofertiliser was employed, with recorded mean values of 8.25 CFU/mL and 8.50 CFU/mL, respectively. During the initial examination, the observed values ranged from 8.52 to 8.61 CFU/mL across all treatments. In the control group, the bacterial population at T0 exhibited linear growth, with a range of 8.11 to 8.91 CFU/mL.

However, treatment T1 also showed a comparable lower level of microbial population growth, indicating a difference between the applied biofertiliser and NPK fertiliser. In treatments T2 to T4, a relatively higher initial growth of the bacterial population was observed. However, upon conducting the subsequent analysis, a discernible increase in the proliferation of the bacterial population was noted. CFU values were found to be higher in treatments T5, T6 and T7 in comparison to treatments T0 and T1 (Figure 1), but they were found to be lower in treatments that used only biofertiliser and those without chemical fertiliser. Following the completion of the 45-day therapeutic regimen, an increase in the

Table 2
Microbial population growth of different treated soils over a span of four months with an interval of 45 days

Treatments	1st B.P.R*	1st log CFU/ mL	2nd B.P. R	2nd log CFU/mL	3rd B.P. R	3rd log CFU/mL	4th B.P. R	4th log CFU/mL
T0	13±1.00	8.11±0.03	15.66±1.52	8.11±0.03	16.33±2.51	8.20±0.06	18±2.64	8.25±0.06
T1	28±1.00	8.44±0.01	30.33±0.57	8.44±0.01	32.00±1.00	8.50±0.01	32±1.00	8.50±0.01
T2	34.66±1.52	8.53±0.01	51.33±4.93	8.53±0.01	56.33±5.85	8.74±0.04	64.33±1.52	8.80±0.01
T3	35.33±6.02	8.54±0.07	48.66±7.02	8.54±0.07	57.00±10.44	8.75±0.08	70±9.53	8.84±0.06
T4	41.66±1.52	8.61±0.01	60.66±8.38	8.61±0.01	68.00±8.71	8.82±0.05	81.66±1.52	8.91±0.01
T5	33.33±2.88	8.52±0.03	56.66±5.68	8.52±0.03	68.33±7.02	8.83±0.04	79.66±6.65	8.90±0.03
T6	37.66±2.30	8.57±0.02	48.00±9.64	8.57±0.02	54.33±6.11	8.73±0.04	68.66±3.05	8.83±0.01
T7	32.66±3.78	8.51±0.04	56.66±3.21	8.51±0.04	66.33±2.51	8.82±0.01	76±4.00	8.88±0.02

Note. *B.P. R= Bacteria production reading, T0 - No fertiliser, T1- Normal fertiliser (NPK Green), T2 - 25 mL Biofertiliser, T3 - 50 mL Biofertiliser, T4 - 100 mL Biofertiliser, T5 - T2 + 50% NPK Green, T6 - T3 + 50% NPK Green, T7 - T4 + 50% NPK Green)

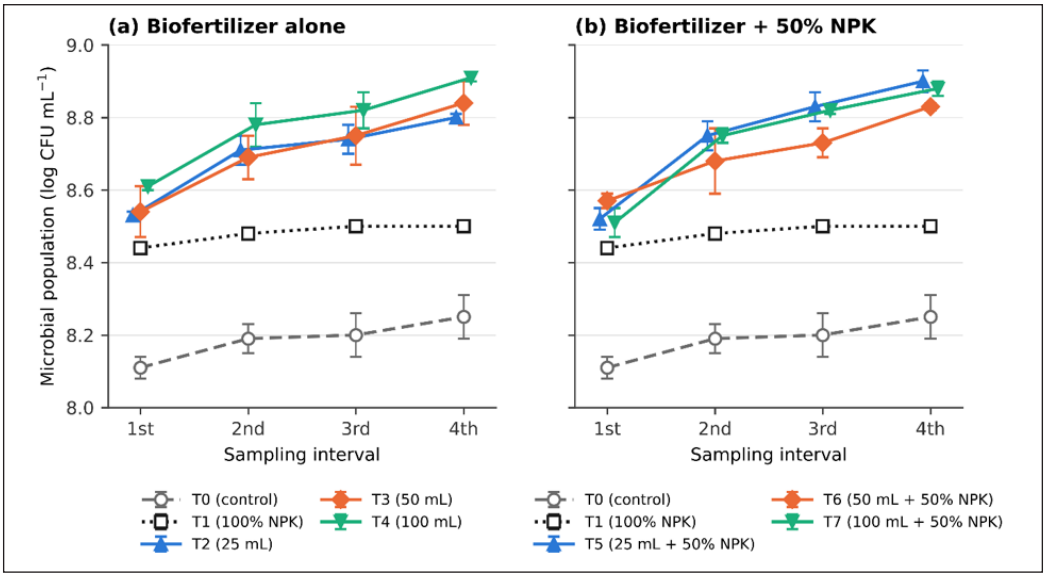


Figure 1. Microbial population growth in soil under various treatments over a four-month period, assessed at 45-day intervals: a) Biofertiliser alone, b) Biofertiliser + 50% NPK

proliferation of the bacterial population was observed in all treatments from T2 to T7. Following a 90-day treatment period, a subsequent decline in the growth of the bacterial population was observed. As an illustration of T2, the CFU value was 8.53 CFU/mL at 45 days, and the later measurement was 8.74 CFU/mL at 90 days, showing a decline in value as compared to the previous value. The growth rate decreased for most of the treatment, but it appears to have recovered after 135 days, when a significant increase was observed. This decline may be attributed to a multitude of factors, such as microbial adaptation, fluctuations in microbial nutrient availability, or alterations in the overall ecological equilibrium of the soil system over a given period. As previously mentioned, these soil microorganisms coexist within the rhizosphere, engaging in competitive interactions for nutrient acquisition, thereby setting up their rhizo-competence (Zboralski & Filion, 2020). Competition between microbial species can reduce microbial diversity in certain settings. Such competition for nutrients and niche space among indigenous and introduced microorganisms can temporarily suppress the population of an inoculated strain, as certain microbial taxa can dominate their habitats, analogous to weeds in plant communities (Cray et al., 2013).

In the final interval, T4 remained the most effective treatment, recording the highest B.P.R. (81.66) and log CFU/mL (8.91) (Table 2). T5 (79.66, 8.90) and T7 (76, 8.88) closely followed, showing strong microbial populations. T0, as expected, displayed the lowest values (18, 8.25). The superior performance of T4 and T5 suggests that these formulations optimised bacterial proliferation, likely due to improved nutrient availability and favorable rhizosphere conditions.

In the third interval, bacterial populations increased significantly across all treatments. T4 achieved the highest B.P.R. (68.00) and log CFU/mL (8.82), followed by T3 (57.00, 8.75) and T5 (68.33, 8.83). T0 continued to lag with the lowest B.P.R. (16.33) and log CFU/mL (8.20). These findings demonstrate that the biofertiliser formulations not only sustained microbial populations but also amplified them over time, especially in the 100 mL biofertiliser treatment. However, *Pseudomonas aeruginosa* GRC1*,* an isolate originating from the potato rhizosphere, showed remarkable rhizosphere competence and showed a stable presence within the rhizosphere ecosystem, while maintaining harmonious coexistence with the indigenous bacterial population (Pandey et al., 2005). In this context, we can hypothesise that the utilisation of our biofertiliser, treated with the modified *Pseudomonas aeruginosa* AGKT1 strain, may increase the competency within the rhizosphere, leading to a reduction, but later microbial proliferation increased within the treated soil.

In the first interval, the bacterial population ratio (B.P.R) and log CFU/mL values varied significantly among treatments. During the second interval, bacterial populations continued to expand, with T4 maintaining its position as the highest-performing treatment (B.P.R: 60.66; log CFU/mL: 8.61). T2 (51.33, 8.53) and T5 (56.66, 8.52) also exhibited strong bacterial proliferation. T0 again recorded the lowest values (15.66, 8.11). The consistent performance of T4 suggests its formulation supports stable microbial growth, due to its balanced nutrient composition and enhanced rhizosphere colonisation. Moreover, the microbial population in T6 and T7 revealed comparatively lower values (3rd and 4th readings) because of chemical fertiliser, which may negatively affect the microbial flora-fauna ecosystem in the soil (Backer et al., 2018; Basu et al., 2021; Singh et al., 2021).

In our experiment, after isolation of the microbe from the rhizosphere, it showed a green colour pigment, which is a sign of the presence of *Pseudomonas aeruginosa* AGKT1 (Pandey et al., 2005). The observed microbial presence confirms successful colonisation of the rhizosphere by the selected strain. Consistent with previous findings, such colonisation enhances soil nutrient availability through the secretion of organic acids that solubilise insoluble mineral fractions and the production of phosphatases and phytases that mineralise organic phosphorus. Additionally, the microorganism facilitates the mobilisation of potassium and zinc, with the magnitude of these effects influenced by soil aggregation and the presence of organic amendments (Muniroh et al., 2019; Rajawat et al., 2016; Sammauria et al., 2020).

Effect of Biofertiliser on Total N, P and Available P

Oil palm seedlings require an adequate level of macronutrients to achieve optimal growth and yield, which can be achieved through the application of biofertiliser (Keni et al., 2023). The presence of soil nutrients, including total N, P and available P**,** after the application

of newly formulated *Pseudomonas aeruginosa* AGKT1-based biofertiliser in oil palm seedlings are presented in Table 3. The highest mean total nitrogen content was observed in T4 (0.295%), which was statistically similar to T7 (0.263%) and T6 (0.233%).

Notably, T7 (100 mL biofertiliser + 50% NPK Green) and T6 (50 mL biofertiliser + 50% NPK Green) also recorded significantly higher nitrogen levels and statistically similar values to T4. In contrast, T0 (unfertilised control) and T2 (25 mL biofertiliser alone) recorded lower soil nitrogen contents and were not significantly different. The near-zero nitrogen content in T0 was expected given the complete absence of both chemical and biological nitrogen inputs. The comparably low nitrogen in T2 suggests that a sub-threshold biofertiliser dose of 25 mL was insufficient to establish adequate rhizospheric colonisation or sustain meaningful biological nitrogen fixation activity, particularly without supplementary NPK support.

The newly developed biofertiliser, with a 100 mL volume in T4, exhibited a moderate nitrogen content due to microbial nitrogen fixation. Whereas T1 (100% NPK Green alone) demonstrated lower nitrogen levels but exhibited the highest variability among replicates, reflecting the inconsistent distribution or retention of inorganic nitrogen from chemical fertilisers in the soil, which is susceptible to leaching and volatilisation losses (Zhu & Chen, 2002). Through secreting or solubilising insoluble complex compounds present in the soil, the application of biofertiliser can substitute for the availability of N and other macronutrients in soil. The mineral soil treated with biofertiliser exhibited a notable increase in nitrogen content when compared to soil treated with chemical fertiliser (Ajeng et al., 2020). Sufficient nitrogen facilitates the production of proteins, enzymes, and chlorophyll, hence enhancing the effective transformation of sunlight into energy via photosynthesis (Prasad et al., 2019).

Table 3
Total N, total and available P of different treatments in potting mixture

Treatments	Total Nitrogen %	Total P (mg/kg)	Available P (mg/kg)
T0	0.012±0.01 f	107.33± 3.05 e	10.66±1.16 f
T1	0.19±0.14 bdc	387.00 ± 5.56 a	19.90±2.08 e
T2	0.03±0.01 ef	244.66 ± 6.51 d	25.23±0.72 ed
T3	0.15±0.03 cd	266.33 ± 6.03 d	27.10±4.78 cd
T4	0.29±0.06 a	353.00 ±7.55 b	37.40±7.17 a
T5	0.12±0.01 ed	318.33 ± 6.51 c	32.433±4.76 abc
T6	0.23±0.02 abc	308.33 ± 16.07 c	29.10±0.53 bcd
T7	0.263±0.04 ab	327.66±30.66 c	34.86±3.70 ab

Note. T0 - No fertiliser, T1- Normal fertiliser (NPK Green), T2 - 25 mL Biofertiliser , T3 - 50 mL Biofertiliser , T4 - 100 mL Biofertiliser , T5 - T2 + 50% NPK Green, T6 - T3 + 50% NPK Green, T7 - T4 + 50% NPK Green

For total P, T1 recorded the highest concentration (387 mg/kg) in the potting mixture. It was resulted from the direct addition of inorganic phosphate-containing NPK fertiliser at full dose, which rapidly elevated total soil P through the incorporation of soluble phosphate salts. However, T4 had the second-highest total P (353 mg/kg), which was significantly higher than T5 (318 mg/kg), T7 (327 mg/kg), and T6 (308 mg/kg). These results indicate that the beneficial microorganisms, such as *Pseudomonas* spp. could accelerate the microbial processes through solubilisation to augment the extent of the nutrient's availability, such as phosphorus (Mahmud & Chong, 2021).

T0 (control, 107.33 ± 3.05 mg/kg) recorded the lowest total P, confirming the necessity of external nutrient inputs or microbial inoculation and that inherent soil phosphorus reserves in the growing medium were insufficient to sustain required phosphorus levels. Treatments combining lower NPK dosage with biofertiliser (T5, T6, T7) recorded intermediate total P values in the range of 308.33-327.66 mg/kg. High levels of total P are not necessarily transformed into equivalent plant-available P, as a substantial proportion of inorganic phosphate becomes immobilised through precipitation and adsorption reactions with soil minerals (Alori et al., 2017; Rodríguez & Fraga, 1999). Our experimental findings indicate that *P. aeruginosa* AGKT1 at the highest application rate effectively mobilised and increased total soil phosphorus, even in the absence of chemical fertiliser. Phosphate-solubilising *Pseudomonas* species convert unavailable inorganic phosphate to soluble forms by secreting organic acids including citric, oxalic, succinic, tartaric, and malic acids in the soil rhizosphere (Singh et al., 2021). Utilising a consortium of microbes in combination with synthetic fertiliser has been shown to effectively improve the overall and accessible phosphorus levels in soil (Keni et al., 2023).

Total P represents the overall phosphorus pool in the soil, while available P is the agronomically critical fraction directly accessible to plant roots for uptake. Results revealed a highly significant treatment effect on soil available P, with treatment means ranging from 10.66 mg/kg (T0) to 37.40 mg/kg (T4). T4 recorded the highest available P (37.40 mg/kg), significantly exceeding T0, T1, T2, and T3, and was statistically comparable only to T7 (34.86 mg/kg) and T5 (32.43 mg/kg). These results showed a considerable agronomic significance, as T4 achieved the highest plant-available P without any chemical fertiliser input, relying entirely on the phosphate-solubilising capacity of *P. aeruginosa* AGKT1. Critically, available P (37.40 mg/kg) in T4 substantially exceeded that of T1 (100% NPK, 19.90 mg/kg), despite T1 recording the highest total P overall. This divergence highlights a well-recognised limitation of inorganic phosphate fertilisers: their tendency to be rapidly fixed in the soil through precipitation with Ca, Fe, and Al ions, rendering a significant proportion of applied P unavailable for plant uptake (Alori et al., 2017; Kalayu, 2019). T7 (100 mL biofertiliser + 50% NPK, 34.86 mg/kg) and T5 (25 mL biofertiliser + 50% NPK, 32.433 mg/kg) also recorded elevated available P, which is statistically similar to T4. T0 (10.66 mg/kg) recorded the lowest available P, consistent with the absence of any

phosphorus input or phosphate-mobilising microbial activity. The release of these low-molecular-weight organic acids by P. *aeruginosa* AGKT1 likely dissolved mineral-bound phosphate complexes in the soil, elevating measurable total P concentrations (Sharma et al., 2013).

According to our study, T1 showed the highest Total P, whereas available P was dominated by T4, indicating that P. *aeruginosa* AGKT1 likely increased phosphorus abundance in the soil compared with chemical fertiliser alone. Phosphorus solubilisation via phosphate-solubilising bacteria provides a sustainable strategy to release unavailable or precipitated soil P in a plant-available form, with organic acid production being one of the key mechanisms by which *Pseudomonas* and related genera release bound phosphorus from mineral complexes (Kalayu, 2019).

Effect of Biofertiliser on Available B, Zn and Mg in Soil

The presence of micronutrients in the soil is crucial for the vigorous growth of oil palm seedlings. Micronutrients such as zinc, manganese, boron, iron, copper, and molybdenum are essential for carrying out important biochemical and physiological activities in oil palm plants (Woittiez et al., 2017). Boron is a critical micronutrient; its deficiency impairs root development, nitrogen absorption, and cell wall integrity, with over 90% of plant B residing in the cell wall, underscoring its structural and metabolic indispensability for establishing healthy root architecture (Srivastava et al., 2025).

Significant treatment differences were observed, with mean soil B concentrations ranging from 1.066 mg/kg (T0) to 3.51 mg/kg (T6). T6 (50 mL biofertiliser + 50% NPK Green, 3.51 mg/kg) recorded the highest soil boron concentration among T0, T1, T2, and T3. From Table 4, we can observe that, T5 (25 mL biofertiliser + 50% NPK Green, 3.07 mg/kg) and T7 (100 mL biofertiliser + 50% NPK Green, 3.06 mg/kg) recorded statistically similar B concentrations to T6. Further, results revealed that combined application of biofertiliser and chemical fertiliser produced comparably higher soil B levels. Previous studies suggested that application of biofertiliser increases the availability of boron, which is essential for the growth and development of plants (Zainuddin et al., 2022).

This trend clearly demonstrates that the combination of P. *aeruginosa* AGKT1 with reduced-dose NPK fertiliser consistently enhanced soil B availability more effectively than applied alone. T4 (100 mL biofertiliser alone, 2.84 mg/kg) recorded significantly higher B than T0, T1, T2, and T3, confirming that *P. aeruginosa* AGKT1 alone, without chemical fertiliser, contributed to soil B enrichment. In contrast, T0 (1.066 mg/kg) recorded the lowest soil B. Further, T1 (100% NPK Green, 1.876 mg/kg), T2 (25 ml biofertiliser, 1.85 mg/kg) and T3 (50 ml biofertiliser, 1.59 mg/kg) showed statistically similar B levels.

From Table 4, we can observe significant treatment differences, with mean soil Zn values ranging from 2.20 mg/kg (T6) to 4.18 mg/kg (T1). T1 (100% NPK Green, 4.18 mg/kg)

recorded the highest soil Zn content, which is statistically similar to T4 (100 mL biofertiliser alone, 3.84 mg/kg). The high soil Zn in T1 likely reflects the zinc content naturally present within the NPK Green (15:15:15) formulation or its carrier compounds. In contrast, T4 achieved comparably high soil Zn (3.84 mg/kg) without any NPK input, suggesting active zinc mobilisation by P. *aeruginosa* AGKT1 through biological mechanisms. T6 (2.20 mg/kg) recorded the lowest residual soil Zn. A previous experimental study suggests that P. *aeruginosa* effectively enhanced plant growth by solubilising zinc and phosphorus minerals present in the soil, with its Zn and P solubilisation ability facilitating the conversion of soil-unavailable mineral forms into plant-accessible forms (Sunitha Kumari et al., 2023). The mechanism involves secretion of siderophores and low-molecular-weight organic acids by *P. aeruginosa*, which chelate and dissolve mineral-bound zinc complexes, releasing Zn^{2+} ions into the rhizosphere solution (Krishnan Kutty et al., 2025). A close association between siderophore production capability and zinc solubilisation has been established in *Pseudomonas* strains, demonstrating that siderophore-producing PGPR significantly increase plant growth parameters including height, fresh weight, and dry weight in zinc-deficient soils (Gao et al., 2021).

Table 4
Availability of B, Zn, and Mg in many different types of treated potting mixture

Treatment Number	B (mg/kg)	Zn (mg/kg)	Mg (mg/kg)
T0	1.066±0.06 d	3.203±0.62 bc	19.63±2.31 c
T1	1.876±0.22 c	4.18±0.49 a	24.79±3.01 bc
T2	1.85±0.08 c	2.71±0.33 cd	33.98±2.34 ab
T3	1.59±0.20 c	2.73±0.34 cd	31.67±9.62 ab
T4	2.84±0.55 b	3.84±0.45 ab	35.14±9.97 ab
T5	3.07±0.14 ab	3.25±0.56 bc	26.41±4.70 bc
T6	3.51±0.31 a	2.20±0.26 d	33.32±3.97 ab
T7	3.06±0.16 ab	2.48±0.35 cd	40.55±8.60 a

Note. T0 - No fertiliser , T1- Normal fertiliser (NPK Green), T2 - 25 mL Biofertiliser , T3 - 50 mL Biofertilise, T4 - 100 mL Biofertiliser , T5 - T2 + 50% NPK Green, T6 - T3 + 50% NPK Green, T7 - T4 + 50% NPK Green

PGPR-based biofertilisers have been shown to enhance the availability of nutrients including nitrogen, phosphorus, potassium, sulphur, zinc, and iron through innovative biological strategies, with PGPR mobilising mineral nutrients that would otherwise remain locked in unavailable soil forms (Wang & Xu, 2026). Deficiency of Mg can hinder the production of chlorophyll and limit the effectiveness of photosynthesis, which ultimately results in a reduction in the overall development of the plant (Putra et al., 2016). In our experiment, the treatment results showed soil Mg values ranging from 19.63 mg/kg (T0) to 40.55 mg/kg (T7), representing more than a twofold increase between the lowest- and

highest-performing treatments. T7 (100 mL biofertiliser + 50% NPK Green, 40.55 mg/kg) recorded the highest soil Mg content and was assigned the highest statistical value, being significantly higher than T0, T1, and T5. Importantly, T7 did not differ significantly from T2 (33.98 mg/kg), T3 (31.67 mg/kg), T4 (35.14 mg/kg), and T6 (33.32 mg/kg), showing similar Mg levels. These results suggest that the integration of biofertilisers enhances the potential to optimise the performance of beneficial microorganisms while also improving the availability of magnesium in the soil (Sani et al., 2022; Yadav et al., 2021).

The superiority of T7 in soil Mg accumulation underscores the synergistic benefit of combining the maximum biofertiliser dose with reduced NPK application. T4 (100 mL biofertiliser alone, 35.14 mg/kg) and T2 (25 mL biofertiliser alone, 33.98 mg/kg) recorded elevated soil Mg levels comparable to T7, demonstrating that the biofertiliser component alone is capable of substantially increasing soil Mg availability across a range of application doses. In contrast, T0 (unfertilised control, 19.63 mg/kg) recorded the lowest soil Mg, confirming severely limited Mg availability in untreated soil. T1 (100% NPK, 24.79 mg/kg) and T5 (26.41 mg/kg) formed an intermediate grouping, both significantly lower than T7. Magnesium, as the central atom of the chlorophyll molecule and a cofactor for numerous phosphate-transferring enzymes, is indispensable for photosynthetic efficiency and carbohydrate metabolism in oil palm seedlings (Cakmak & Kirkby, 2008; Gransee & Führs, 2013). While Mg solubilisation is less extensively studied than P or Zn mobilisation by *Pseudomonas* spp., the organic acid production and mineral weathering activity of *P. aeruginosa* AGKT1 likely facilitated the release of Mg^{2+} ions from soil mineral complexes, particularly from magnesium silicates and carbonates prevalent in tropical soils (Sindhu et al., 2016). Additionally, the improvement in overall soil organic matter quality associated with PGPR rhizosphere activity enhances cation exchange capacity (CEC), which in turn promotes Mg^{2+} retention and availability in the soil profile (Bhattacharyya & Jha, 2012).

Most Effective Treatments

In our experimental study, T4 (100 mL biofertiliser alone, 8.91 log CFU/mL) recorded the highest soil microbial population, followed closely by T5 (25 mL biofertiliser + 50% NPK, 8.90 log CFU/mL). From Table 5, we can observe that the marginal difference between T4 and T5 indicates that a lower biofertiliser dose combined with reduced chemical fertiliser can sustain rhizospheric microbial populations comparable to those of the highest standalone biofertiliser application.

The dominance of T4 in soil N accumulation reflects the biological nitrogen fixation (BNF) activity of *P. aeruginosa* AGKT1 with highest microbial counts in T4 reflect the strong capacity of the nitrogenase enzyme complex responsible for converting atmospheric N_2 into plant-assimilable ammonium (NH_4^+) (Bhattacharyya & Jha, 2012; Shameer & Prasad, 2018). In terms of soil phosphorus, the proximity of T7 (2nd rank) to T4 suggests

Table 5
Summary of the best-performing treatments (1st and 2nd rank) across all measured soil parameters

Parameter	1st Best Value Treatment	2nd Best Value Treatment
Microbial population growth	T4= 8.91±0.01 CFU/ml	T5= 8.90±0.03 CFU/ml
Total Nitrogen %	T4= 0.29±0.06 %	T7= 0.263±0.04%
Total P (mg/kg)	T1= 387.00±5.56 mg/kg	T4= 353.00±7.55 mg/kg
Available P (mg/kg)	T4= 37.40±7.18 mg/kg	T7= 34.86±3.70 mg/kg
B (mg/kg)	T6= 3.51±0.31 mg/kg	T5= 3.07±0.14 mg/kg
Zn (mg/kg)	T1= 4.18±0.49 mg/kg	T4= 3.84±0.45 mg/kg
Mg (mg/kg)	T7= 40.55±8.60 mg/kg	T4= 35.14±9.97 mg/kg

Note. T0 - No fertiliser, T1- Normal fertiliser (NPK Green), T2 - 25 mL Biofertiliser, T3 - 50 mL Biofertiliser, T4 - 100 mL Biofertiliser, T5 - T2 + 50% NPK Green, T6 - T3 + 50% NPK Green, T7 - T4 + 50% NPK Green

that the combination of maximum biofertiliser dose with reduced NPK maintains competitive N levels in soil, supporting integrated nutrient management strategies. On the contrary, T1 (100% NPK Green, 387.00 ± 5.56 mg/kg) recorded the highest total soil phosphorus, with T4 (100 mL biofertiliser alone, 353.00 ± 7.549 mg/kg) ranking second. The highest total P in T1 is directly attributable to the large inorganic phosphate input from the full-dose NPK Green application, which immediately elevates the total soil P pool through the incorporation of soluble phosphate salts. In contrast, high total P in T4 was achieved entirely without chemical fertiliser and with the highest microbial presence in soil, attributable to the phosphate solubilisation activity of *P. aeruginosa* AGKT1, which produces organic acids including citric, gluconic, and oxalic acids that dissolve mineral-bound phosphate complexes (Singh et al., 2021). For available phosphorus, T4 (100 mL biofertiliser alone, 37.40 ± 7.175 mg/kg) recorded the highest, followed by T7 (100 mL biofertiliser + 50% NPK, 34.86 ± 3.70 mg/kg).

Despite exhibiting the highest population of *Pseudomonas aeruginosa* AGKT1 and elevated concentrations of major nutrients, including total nitrogen, total phosphorus, and available phosphorus, treatment T4 produced comparatively lower micronutrient accumulation except for Zinc. In our experimental study, the overall result shows a positive impact of implementing biofertiliser; a previous experiment also suggested that PGPR inoculation on oil palm seedlings under field nursery conditions has been demonstrated to significantly enhance nitrogen accumulation in plant tissues and improve total soil nitrogen status compared to unfertilised controls (Amir et al., 2005).

CONCLUSION

Among the analysed soil parameters, T4 (100 mL *Pseudomonas aeruginosa* AGKT1 biofertiliser alone) emerged as the most consistently superior treatment, ranking first in four parameters (microbial population growth, total N, available P, and Zn) and second in

two further parameters (total P and Mg). This treatment achieved these outcomes without any chemical fertiliser input, demonstrating the comprehensive capacity of P. *aeruginosa* AGKT1 to enhance soil nutrients under maximum standalone application. T7 (100 mL biofertiliser + 50% NPK) ranked first in Mg and second in both total N and available P, representing the most effective integrated biofertiliser-chemical fertiliser treatment. These findings reinforce the feasibility of integrating bio-based approaches into mainstream plantation management for more ecologically balanced and cost-effective agricultural practices. Based on this study, *Pseudomonas aeruginosa* AGKT1-based biofertiliser, applied at the highest dose (100 mL) alone or in combination with 50% NPK Green, consistently produced higher values for total soil N, available P, Zn, and Mg, highlighting the greater efficiency of biologically mediated nutrient solubilisation over inorganic fertiliser addition in enhancing plant accessibility. Future research should focus on field-scale validation and long-term effects of such formulations to support wide-scale adoption in sustainable oil palm production systems.

ACKNOWLEDGEMENT

This work was supported under research grant FRGS 5540305. The authors thank the Ministry of Higher Education Malaysia (MOHE) and Universiti Putra Malaysia for sponsoring this research.

REFERENCES

Adileksana, C., Yudono, P., Purwanto, B. H., & Wijoyo, R. B. (2020). The growth performance of oil palm seedlings in pre-nursery and main nursery stages as a response to the substitution of NPK compound fertiliser and organic fertiliser. *Caraka Tani: Journal of Sustainable Agriculture, 35*(1), 89-97. https://doi.org/10.20961/carakatani.v35i1.33884

Ajeng, A. A., Abdullah, R., Malek, M. A., Chew, K. W., Ho, Y. C., Ling, T. C., Lau, B. F., & Show, P. L. (2020). The effects of biofertilisers on growth, soil fertility, and nutrient uptake of oil palm (*Elaeis guineensis*) under greenhouse conditions. *Processes, 8*(12), Article 1681. https://doi.org/10.3390/pr8121681

Alori, E. T., Glick, B. R., & Babalola, O. O. (2017). Microbial phosphorus solubilisation and its potential for use in sustainable agriculture. *Frontiers in Microbiology, 8*, Article 971. https://doi.org/10.3389/fmicb.2017.00971

Amir, H. G., Shamsuddin, Z. H., Halimi, M. S., Marziah, M., & Ramlan, M. F. (2005). Enhancement in nutrient accumulation and growth of oil palm seedlings caused by PGPR under field nursery conditions. *Communications in Soil Science and Plant Analysis, 36*(15-16), 2059-2066. https://doi.org/10.1080/00103620500194270

Backer, R., Rokem, J. S., Ilangumaran, G., Lamont, J., Praslickova, D., Ricci, E., Subramanian, S., & Smith, D. L. (2018). Plant growth-promoting rhizobacteria: Context, mechanisms of action, and roadmap to commercialisation of biostimulants for sustainable agriculture. *Frontiers in Plant Science, 9*, Article 1473. https://doi.org/10.3389/fpls.2018.01473

Basu, A., Prasad, P., Das, S. N., Kalam, S., Sayyed, R. Z., Reddy, M. S., & El Enshasy, H. (2021). Plant growth-promoting rhizobacteria (PGPR) as green bioinoculants: Recent developments, constraints, and prospects. *Sustainability, 13*(3), Article 1140. https://doi.org/10.3390/su13031140

Berrow, M. L., & Stein, W. M. (1983). Extraction of metals from soils and sewage sludges by refluxing with aqua regia. *Analyst, 108*(1283), 277-285. https://doi.org/10.1039/an9830800277

Bhattacharyya, P. N., & Jha, D. K. (2012). Plant growth-promoting rhizobacteria (PGPR): Emergence in agriculture. *World Journal of Microbiology and Biotechnology, 28*(4), 1327–1350. https://doi.org/10.1007/s11274-011-0979-9

Cakmak, I., & Kirkby, E. A. (2008). Role of magnesium in carbon partitioning and alleviating photooxidative damage. *Physiologia Plantarum, 133*(4), 692-704. https://doi.org/10.1111/j.1399-3054.2007.01042.x

Cray, J. A., Bell, A. N. W., Bhaganna, P., Mswaka, A. Y., Timson, D. J., & Hallsworth, J. E. (2013). The biology of habitat dominance: Can microbes behave as weeds? *Microbial Biotechnology, 6*(5), 453-492. https://doi.org/10.1111/1751-7915.12027

Dasila, H., Sah, V. K., Jaggi, V., Kumar, A., Tewari, L., Taj, G., Chaturvedi, S., Perveen, K., Bukhari, N. A., Siang, T. C., & Sahgal, M. (2023). Cold-tolerant phosphate-solubilising *Pseudomonas* strains promote wheat growth and yield by improving soil phosphorus (P) nutrition status. *Frontiers in Microbiology, 14*, Article 1135693. https://doi.org/10.3389/fmicb.2023.1135693

Duhan, P., & Kataria, R. (2022). Biofertilisers for sustainable agriculture. In C. Baskar, S. Ramakrishna, & A. D. La Rosa (Eds.), *Encyclopedia of green materials* (pp. 1–13). Springer. https://doi.org/10.1007/978-981-16-4921-9_237-1

Gransee, A., & Führs, H. (2013). Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilisation and root uptake under adverse growth conditions. *Plant and Soil, 368*, 5-21. https://doi.org/10.1007/s11104-012-1567-y

Hernández-Fernández, M., Cordero-Bueso, G., Ruiz-Muñoz, M., & Cantoral, J. M. (2021). Culturable yeasts as biofertilisers and biopesticides for sustainable agriculture: A comprehensive review. *Plants, 10*(5), Article 822. https://doi.org/10.3390/plants10050822

Kalayu, G. (2019). Phosphate-solubilising microorganisms: Promising approach as biofertilisers. *International Journal of Agronomy, 2019*, Article 4917256. https://doi.org/10.1155/2019/4917256

Kamran, S., Shahid, I., Baig, D. N., Rizwan, M., Malik, K. A., & Mehnaz, S. (2017). Contribution of zinc-solubilising bacteria in growth promotion and zinc content of wheat. *Frontiers in Microbiology, 8,* Article 2593. https://doi.org/10.3389/fmicb.2017.02593

Keni, M. F., Zainuddin, N., & Masri, M. M. M. (2023). Improving the growth performance of oil palm seedlings by mixtures of organic and chemical fertilisers. *Journal of Oil Palm Research, 35*(1), 147-156. https://doi.org/10.21894/jopr.2022.0033

Mahmud, M. S., & Chong, K. P. (2021). Formulation of biofertilisers from oil palm empty fruit bunches and plant growth-promoting microbes: A comprehensive and novel approach towards plant health. *Journal of King Saud University - Science, 33*, Article 101647. https://doi.org/10.1016/j.jksus.2021.101647

Gao, H., Gao, Y., Zhang, F., Liu, B., Ji, C., Xue, J., Yuan, L., & Li, R. (2021). Functional characterization of an novel acyl-CoA: Diacylglycerol acyltransferase 3-3 (CsDGAT3-3) gene from *Camelina sativa*. *Plant Science, 303*, Article110752. https://doi.org/10.1016/j.plantsci.2020.110752

Mohamad, S. A., Masri, M. M. M., Kamarudin, N., Sulaiman, M. R., Costa, A., Ong-Abdullah, M., Othman, H., Ahmad, S. N., Syarif, M. N. Y., Karim, Z. A., Ghani, I. A., Amit, S., Zakaria, A., Ming, S. C., Chuan, S. T., Jalinas, J., Koong, Y. Y., Sairi, A. A., Ali, S. M. F. S., Abdullah, M., Annamalai, S., Hung, K. J., Mohammed, M. A., Seman, I. A., Moslim, R., & Parveez, G. K. A. (2023). Impact of *Elaeidobius kamerunicus* (Faust) introduction on oil palm fruit formation in Malaysia and factors affecting its pollination efficiency: A review. *Journal of Oil Palm Research, 35*(1), 1-22. https://doi.org/10.21894/jopr.2022.0021

Muniroh, M. S., Nusaibah, S. A., Vadamalai, G., & Siddique, Y. (2019). Proficiency of biocontrol agents as plant growth promoters and hydrolytic enzyme producers in *Ganoderma boninense*-infected oil palm seedlings. *Current Plant Biology, 20*, Article 100116. https://doi.org/10.1016/j.cpb.2019.100116

Nadeem, S. M., Naveed, M., Ayyub, M., Khan, M. Y., Ahmad, M., & Zahir, Z. A. (2016). Potential, limitations and future prospects of *Pseudomonas* spp. for sustainable agriculture and environment: A review. *Soil and Environment, 35*(2), 106-145. https://www.cabidigitallibrary.org/doi/pdf/10.5555/20173014117

Naureen, Z., Aqeel, M., Hassan, M. N., Gilani, S. A., Bouqellah, N., Mabood, F., Hussain, J., & Hafeez, F. Y. (2015). Isolation and screening of silicate bacteria from various habitats for biological control of phytopathogenic fungi. *American Journal of Plant Sciences, 6*(18), 2850-2859. https://doi.org/10.4236/ajps.2015.618282

Nusaibah, S. A., Saad, G., & Hun, T. G. (2017). Antagonistic efficacy of *Trichoderma harzianum* and *Bacillus cereus* against Ganoderma disease of oil palm via dip, place and drench (DPD) artificial inoculation technique. *International Journal of Agriculture and Biology, 19*(2), 299-306. https://doi.org/10.17957/IJAB/15.0280

Okalebo, J. R., Gathua, K. W., & Woomer, P. L. (1993). *Laboratory methods of soil and plant analysis: A working manual*. (2nd ed.). Soil Science Society of East Africa.

Pandey, P., Kang, S. C., Gupta, C. P., & Maheshwari, D. K. (2005). Rhizosphere-competent *Pseudomonas aeruginosa* GRC1 produces characteristic siderophore and enhances growth of Indian mustard (*Brassica campestris*). *Current Microbiology, 51*, 303-309. https://doi.org/10.1007/s00284-005-0014-1

Parveez, G. K. A., Hishamuddin, E., Loh, S. K., Ong-Abdullah, M., Salleh, K. M., Bidin, M. N. I. Z., Sundram, S., Hasan, Z. A. A., & Idris, Z. (2020). Oil palm economic performance in Malaysia and R&D progress in 2019. *Journal of Oil Palm Research, 32*(2), 159-190. https://doi.org/10.21894/jopr.2020.0032

Parvin, W., Rahman, M. M., Govender, N. T., & Wong, M. Y. (2020). Identification, determination and quantification of indole-3-acetic acid produced by *Pseudomonas aeruginosa* UPMP3 and its effect on the growth of oil palm (*Elaeis guineensis* Jacq.). *World Journal of Agricultural Research, 8*(5), 75-83. https://www.sciepub.com/wjar/abstract/11959

Srivastava, A., Thakur, M., Pandey, S., Kumar, C., Sharma, S., Deshmukh, R., Sharma, A., Singh, V. P., & Tripathi, D. K. (2025). Functions of boron in plant roots: Current insights. *South African Journal of Botany, 177*, 201-210. http://cuh.ndl.gov.in/handle/123456789/1819

Sharpley, A. N. (2009). Bioavailable phosphorus in soil. In J. L. Kovar & G. M. Pierzynski (Eds.), *Methods of phosphorus analysis for soils, sediments, residuals, and waters* (2nd ed., pp. 38-43). Southern Cooperative Series Bulletin No. 408.

Prasad, M., Srinivasan, R., Chaudhary, M., Choudhary, M., & Jat, L. K. (2019). Plant growth-promoting rhizobacteria (PGPR) for sustainable agriculture: Perspectives and challenges. In *PGPR amelioration in sustainable agriculture* (pp. 129-157). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-815879-1.00007-0

Putra, E. T. S., Issukindarsyah, Taryono, Purwanto, B. H., & Indradewa, D. (2016). Role of boron and silicon in inducing mechanical resistance of oil palm seedlings to drought stress. *Journal of Applied Sciences, 16*(6), 242–251. https://doi.org/10.3923/jas.2016.242.251

Qaim, M., Sibhatu, K. T., Siregar, H., & Grass, I. (2020). Environmental, economic, and social consequences of the oil palm boom. *Annual Review of Resource Economics, 12*, 321-344. https://doi.org/10.1146/annurev-resource-110119-024922

Raja Abd. Rahman, R. N. Z., Salleh, A. B., Basri, M., & Abu Samad, M. Y. (2014). *Biofertiliser* (International Patent Application No. WO2014/042517 A2; PCT/MY2013/000168). World Intellectual Property Organization.

Rajawat, M. V. S., Singh, S., Tyagi, S. P., & Saxena, A. K. (2016). A modified plate assay for rapid screening of potassium-solubilising bacteria. *Pedosphere, 26*(5), 768-773. https://doi.org/10.1016/S1002-0160(15)60080-7

Rodríguez, H., & Fraga, R. (1999). Phosphate-solubilising bacteria and their role in plant growth promotion. *Biotechnology Advances, 17*(4-5), 319-339. https://doi.org/10.1016/S0734-9750(99)00014-2

Roslan, N. A., Othman, N. M. I., Mohidin, H., Zuan, T. K., Munir, J., El Pabrian, D., Abu Samah, S. N. A., & Sadikan, S. F. N. (2025). *In vitro characterisation and identification of a plant growth-promoting bacteria consortium from Malaysian oil palm (Elaeis guineensis) rhizosphere as a potential sustainable biofertilizer*, *16*(2). https://doi.org/10.37231/jab.2025.16.2.398

Sah, S., Krishnani, S., & Singh, R. (2021). *Pseudomonas*-mediated nutritional and growth-promotional activities for sustainable food security. *Current Research in Microbial Sciences, 2*, Article 100084. https://doi.org/10.1016/j.crmicr.2021.100084

Salisu, B., & Sani, I. (2024). Biofertiliser production using phosphate-solubilising *Pseudomonas* species isolated from rhizosphere soil: Towards indigenous biofertiliser for enhanced crop productivity in Katsina, Nigeria. *UMYU Journal of Microbiology Research, 9*(1), 123-133. https://doi.org/10.47430/ujmr.2491.014

Sammauria, R., Kumawat, S., Kumawat, P., Singh, J., & Jatwa, T. K. (2020). Microbial inoculants: Potential tool for sustainability of agricultural production systems. *Archives of Microbiology, 202*, 677-693. https://doi.org/10.1007/s00203-019-01795-w

Sani, I., Kurnia, Y. W., Sinthya, H. C., Anthony, R., Situmorang, E. C., Utomo, C., & Liwang, T. (2022). Exploring the potency of microalgae-based biofertiliser and its impact on oil palm seedling growth. *Agrivita, 44*(1), 139-151. https://doi.org/10.17503/agrivita.v44i1.3102

Shameer, S., & Prasad, T. N. V. K. V. (2018). Plant growth-promoting rhizobacteria for sustainable agricultural practices. *Plant Growth Regulation, 84*, 603-615. https://doi.org/10.1007/s10725-017-0365-1

Sharma, S. B., Sayyed, R. Z., Trivedi, M. H., & Gobi, T. A. (2013). Phosphate-solubilising microbes: Sustainable approach for managing phosphorus deficiency in agricultural soils. *SpringerPlus, 2*, Article 587. https://doi.org/10.1186/2193-1801-2-587

Siddiqui, Y., Surendran, A., Paterson, R. R. M., Ali, A., & Ahmad, K. (2021). Current strategies and perspectives in detection and control of basal stem rot of oil palm. *Saudi Journal of Biological Sciences, 28*(5), 2840-2849. https://doi.org/10.1016/j.sjbs.2021.02.016

Sindhu, S. S., Parmar, P., Phour, M., & Sehrawat, A. (2016). Potassium-solubilising microorganisms (KSMs) and their effect on plant growth improvement. In V. Meena, B. Maurya, J. Verma, & R. Meena. (Eds.), *Potassium-solubilising microorganisms for sustainable agriculture* (pp. 171-185). Springer. https://doi.org/10.1007/978-81-322-2776-2_13

Singh, D., Thapa, S., Geat, N., Mehriya, M. L., & Rajawat, M. V. S. (2021). Biofertilisers: Mechanisms and application. In *Biofertilisers: Volume 1: Advances in Bio-inoculants* (pp. 151-166). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-821667-5.00024-5

Sunitha Kumari, K., Padma Devi, S. N., Ranjithkumar, R., Djearamane, S., Tey, L.-H., Wong, L. S., Kayarohanam, S., Arumugam, N., Almansour, A. I., & Perumal, K. (2023). Organic remobilization of zinc and phosphorus availability to plants by application of mineral-solubilizing bacteria *Pseudomonas aeruginosa*. *Heliyon, 9*(11), Article e22128. https://doi.org/10.1016/j.heliyon.2023.e22128

Khan, A. u. M., Torelli, A., Wolf, I., & Gretz, N. (2018). AutoCellSeg: Robust automatic colony forming unit (CFU)/cell analysis using adaptive image segmentation and easy-to-use post-editing techniques. *Scientific Reports, 8*, Article 7302. https://doi.org/10.1038/s41598-018-24916-9

Krishnan Kutty, S. K., Skandasamy Natchimuthu, P. D., Ranjithkumar, R., Djearamane, S., Tey, L.-H., Wong, L. S., Kayarohanam, S., Arumugam, N., Almansour, A. I., & Mahalingam, S. M. (2025). Field trial to correlate mineral solubilization activity of *Pseudomonas aeruginosa* and biochemical content of groundnut plants. *Open Life Sciences, 20*(1), Article 20221008. https://doi.org/10.1515/biol-2022-1008

Timmusk, S., Behers, L., Muthoni, J., Muraya, A., & Aronsson, A. -C. (2017). Perspectives and challenges of microbial application for crop improvement. *Frontiers in Plant Science, 8*, Article 49. https://doi.org/10.3389/fpls.2017.00049

Ullah, S., Bano, A., Ullah, A., Shahid, M. A., & Khan, N. (2022). A comparative study of plant growth-promoting rhizobacteria (PGPR) and sowing methods on nutrient availability in wheat and rhizosphere soil under salinity stress. *Rhizosphere, 23*, Article 100571. https://doi.org/10.1016/j.rhisph.2022.100571

Wang, M., & Xu, Z. (2026). PGPR-mediated enhancement of soil nutrients, rhizosphere microbial ecology, and plant growth: A review. *npj Biofilms and Microbiomes, 12*, Article 95. https://doi.org/10.1038/s41522-026-00966-0

Woittiez, L. S., van Wijk, M. T., Slingerland, M., van Noordwijk, M., & Giller, K. E. (2017). Yield gaps in oil palm: A quantitative review of contributing factors. *European Journal of Agronomy, 83*, 57-77. https://doi.org/10.1016/j.eja.2016.11.002

Yadav, A. N., Kour, D., Kaur, T., Devi, R., Yadav, A., Dikilitas, M., Abdel-Azeem, A. M., Ahluwalia, A. S., & Saxena, A. K. (2021). Biodiversity and biotechnological contribution of beneficial soil microbiomes for nutrient cycling, plant growth improvement, and nutrient uptake. *Biocatalysis and Agricultural Biotechnology, 33*, Article 102009. https://doi.org/10.1016/j.bcab.2021.102009

Yang, W., Zhang, X., Wu, L., Rensing, C., & Xing, S. (2021). Short-term application of magnesium fertiliser affected soil microbial biomass, activity, and community structure. *Journal of Soil Science and Plant Nutrition, 21*, 675-689. https://doi.org/10.1007/s42729-020-00392-x

Zainuddin, N., Keni, M. F., & Ibrahim, S. A. S. (2019). Effect of biofertiliser containing different percentage rates of chemical fertiliser on oil palm seedlings. *Journal of Oil Palm Research, 31*(4), 582-591. https://doi.org/10.21894/jopr.2019.0053

Zainuddin, N., Keni, M. F., Ibrahim, S. A. S., & Masri, M. M. M. (2022). Effect of integrated biofertilisers with chemical fertilisers on the oil palm growth and soil microbial diversity. *Biocatalysis and Agricultural Biotechnology, 39*, Article 102237. https://doi.org/10.1016/j.bcab.2021.102237

Zboralski, A., & Filion, M. (2020). Genetic factors involved in rhizosphere colonisation by phytobeneficial *Pseudomonas* spp. *Computational and Structural Biotechnology Journal, 18*, 3539-3554. https://doi.org/10.1016/j.csbj.2020.11.025

Zhu, Z. L., & Chen, D. L. (2002). Nitrogen fertiliser use in China: Contributions to food production, impacts on the environment and best management strategies. *Nutrient Cycling in Agroecosystems, 63*, 117-127. https://doi.org/10.1023/A:1021107026067