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Research Article

Plant growth-promoting rhizobacteria and ash applications enhance tomato yield in Ultisol

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Abstract

Plant growth-promoting rhizobacteria (PGPR) and cattle manure ash applied to Ultisol can enhance soil fertility and tomato productivity. The study aimed to analyze the effects of PGPR and cattle manure ash on the growth and yield of tomato in Ultisol. The experiment was conducted in Kubu Raya Regency, West Kalimantan, Indonesia, from March to July 2025, using a factorial completely randomized design with PGPR application (with and without PGPR) and cattle manure ash (dolomite as control, 5, 10, 15, and 20 ton ha^{-1}). A total of 10 treatment combinations were evaluated, with 3 replications. The PGPR significantly improved physiological performance, growth, and yield of tomato in Ultisol. Nitrogen and phosphorus uptake increased by 0.65 g per plant and 0.23 g per plant, respectively, along with higher relative growth rates. The combination of PGPR and 5 ton ha^{-1} cattle manure ash enhanced plant height and shoot dry weight to levels similar to dolomite, while optimal root dry weight occurred at 10 ton ha^{-1} ash. Fruit number increased at 15 ton ha^{-1} ash, comparable to dolomite, although fruit weight per plant remained slightly lower. The results indicate that cattle manure ash can partially replace dolomite in tomato cultivation, can increase vegetative growth at 5 ton ha^{-1} and certain yield components at higher rates of 10 ton ha^{-1}.

Keywords: microorganisms; nutrient uptake; plant physiology; soil fertility; tomato productivity

Introduction

Tomato (*Solanum lycopersicum* L.) is one of the important horticultural commodities widely cultivated across nearly all regencies and cities in West Kalimantan, playing a strategic role in supporting farmers' income and regional food security (BPS, 2025). However, during the 2021–2024 period, tomato production and productivity in West Kalimantan exhibited a declining trend. Tomato production was recorded at 4,107.54 tons with a productivity of 5.14 ton ha^{-1} in 2021, gradually decreasing to 2,919.63 tons with a productivity of 3.65 ton ha^{-1} in 2024 (BPS, 2025).

Therefore, more effective and sustainable land intensification strategies are required to improve tomato productivity in the region.

Ultisol represents a major agricultural land type in West Kalimantan, covering the largest area of 9.2 million ha, equivalent to 64.83% of the province (BPS, 2019). The limited soil fertility of Ultisol often constrains tomato growth and development, due to acidic soil reaction, relatively low organic matter content, low nutrient availability, and extremely low phosphorus availability caused by fixation by Al^{3+} ions, rendering phosphorus inaccessible to plants (Idwar et al., 2025; Lubis et al., 2023; Rajmi et al., 2018). Consequently, the implementation of appropriate and sustainable cultivation technologies is necessary to enhance Ultisol soil fertility and tomato productivity, particularly through the use of functional microorganisms, namely plant growth-promoting rhizobacteria (PGPR), and ash derived from the combustion of cattle manure fertilizer.

PGPR applied to Ultisol can increase tomato growth and development by colonizing the plant rhizosphere and thriving in the root environment (Basu et al., 2021). These beneficial bacteria contribute to phosphate solubilization, hormone production, and nitrogen fixation (de Andrade et al., 2023; Vocciante et al., 2022), thereby directly enhancing plant physiological processes such as water and nutrient uptake, photosynthesis, and ultimately promoting growth and development (Bhanse et al., 2022; Ilangumaran & Smith, 2017). PGPR also stimulate plant growth by inducing tolerance to biotic and abiotic stresses (Basu et al., 2021).

Cattle manure ash, used in this study as a soil ameliorant, supports the improvement of Ultisol pH, thereby directly increasing nutrient availability for tomato plants. The combustion of manure enhances soil pH, exchangeable cations, and carbon content, while its application can increase soil organic carbon and inorganic nitrogen availability in the forms of NH_4^+–N and NO_3^-–N (Olowoboko et al., 2018). The study aimed to analyze the effects of PGPR and cattle manure ash application on the growth and yield of tomato grown in Ultisol.

Materials and methods

The study was conducted in Kuala Ambawang, Kubu Raya Regency, West Kalimantan, Indonesia, from March to July 2025. The tomato seeds used in this study were of the Servo F1 variety. The Ultisol soil used as the planting medium had the following characteristics: pH 4.96, P_2O_5 11.60 ppm, total N 0.09%, and exchangeable K 0.10 cmol(+) kg^{-1}. The ash derived from burned cattle manure applied in this study had a neutralizing value of 30.13% (Soil Chemistry and Fertility Laboratory, Faculty of Agriculture, Universitas Tanjungpura).

The PGPR used in this study was isolated from the rhizosphere of bamboo roots in Kubu Raya Regency. PGPR isolation was carried out to obtain rhizosphere bacteria, which were subsequently selected and functionally characterized using selective media, namely Ashby and Pikovskaya media, to confirm the presence of nitrogen-fixing and phosphate-solubilizing bacteria (Figure 1). The results on Ashby medium indicated that the bacterial isolates exhibited diverse colony morphologies and good growth performance, with several isolates forming clear zones around the colonies, suggesting active nitrogen fixation, even at a dilution level of 10^9. Furthermore, on Pikovskaya medium, the isolates demonstrated phosphate-solubilizing ability, as indicated by the formation of clear (halo) zones surrounding the colonies, with phosphate solubilization index values ranging from 1 to 5 (moderate to very high category).

In addition, the isolates exhibited morphological diversity, predominantly circular and irregular colony forms, with color variations ranging from white to yellowish.

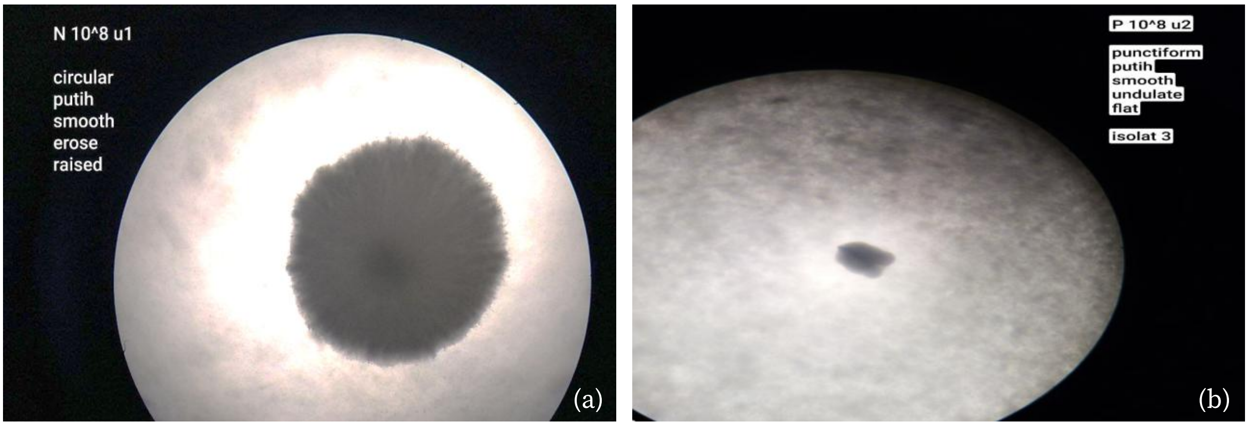

Figure 1. Functional characterization of N-fixing: (a) P-solubilizing; (b) bacteria

The experiment was arranged in a factorial completely randomized design. The first factor was PGPR application, consisting of two levels, namely, without PGPR and with PGPR. The second factor was cattle manure ash, consisting of dolomite as a control and cattle manure ash at rates of 5, 10, 15, and 20 ton ha^{-1}. A total of 10 treatment combinations were evaluated, with 3 replications and 7 sampled plants per experimental unit, resulting in a total of 210 plants.

The planting media were prepared by cleaning and sieving Ultisol, then filling 10 kg of soil into each polybag. Dolomite was applied to the planting media at 13 g per polybag, equivalent to 2.6 ton ha^{-1} (based on soil analysis results). Cattle manure ash was applied according to the treatment levels: 5 ton ha^{-1} (25 g per polybag), 10 ton ha^{-1} (50 g per polybag), 15 ton ha^{-1} (75 g per polybag), and 20 ton ha^{-1} (100 g per polybag). The media were incubated for two weeks before transplanting. Tomato seedlings, 20 days old in the nursery, were transplanted into the prepared media at one seedling per polybag.

The bamboo root rhizosphere, confirmed to contain nitrogen-fixing and phosphate-solubilizing bacteria, was collected and soaked in distilled water for approximately 8 hours, then applied to tomato plants at 7 and 14 days after transplanting (DAT). The roots were soaked overnight prior to application to maintain microbial stability and viability. The PGPR solution was applied at a volume of 250 ml per polybag, while plants without PGPR treatment were irrigated with 250 ml of distilled water per polybag.

NPK fertilizer (15:15:15) was applied after transplanting and at 3 weeks after transplanting (WAT) at a rate of 27 g per plant per application. Staking was installed at 2 WAT. Plants were irrigated routinely in the morning and evening at 250 ml per polybag, except during PGPR application. Weeds in the planting media and experimental area were removed manually on a regular basis. Tomato fruits were harvested eight times at 52, 56, 60, 64, 68, 72, 76, and 80 DAT.

Nitrogen and phosphorus uptake of tomato plants were analyzed at the Soil Chemistry and Fertility Laboratory, Faculty of Agriculture, Tanjungpura University, at 30 DAT. Observations were conducted on one sampled plant per replication for both PGPR-treated and untreated plants. Nitrogen uptake was determined using the Kjeldahl method, while phosphorus uptake was measured using the Bray I extraction method. Relative growth rate (RGR) was evaluated by measuring the dry weight of destructively sampled plants at 7, 14, 21, and 28 DAT. RGR was calculated using the formula: $\mathrm{RGR} = \frac{\ln W_2 - \ln W_1}{t_2 - t_1}$. Note: RGR is the relative growth rate, W_1 and W_2 are the plant dry weights at the first and second observation, and t_1 and t_2 are the corresponding plant ages (Hunt, 2017).

Plant height, root dry weight, and shoot dry weight were measured at 28 DAT. Dry weight measurements were performed destructively by sampling one plant per replication, separating it into root and shoot components. Samples were oven-dried at 90°C for 1 × 24 hours or until constant weight, and then weighed to obtain root and shoot dry weights. Plant height was measured from the base of the stem to the apical tip. Fruit number per plant was recorded from the first to the last harvest, while fruit weight per plant was determined by summing the total fruit weight across all harvests for each sampled plant.

The data were analyzed using analysis of variance (ANOVA) to determine the significant effects of the treatments on the observed variables. When significant effects were detected, an HSD test at a 0.05 significance level was performed to identify differences among treatment levels.

Results and discussion

Nitrogen and phosphorus uptake

Laboratory analysis revealed that tomato plants treated with PGPR exhibited higher nitrogen uptake (0.65 g per plant) compared to those without PGPR (0.29 g per plant). Similarly, phosphorus uptake in PGPR-treated plants was greater (0.23 g per plant) than in plants without PGPR (0.10 g per plant) (Figure 2). This effect is attributed to the role of PGPR in supporting nutrient cycling for plants (Zhang et al., 2024). The bacteria in PGPR are associative symbionts that live and develop outside plant cells, facilitating direct metabolite exchange with the host, providing nutrients, and modulating plant hormone balance. Bacteria from the genus Arthrobacter within PGPR promote plant growth through mechanisms such as enhanced iron uptake via siderophore-mediated chelation and solubilization of inorganic phosphate, which can influence plant signaling pathways and metabolism (Sun et al., 2024).

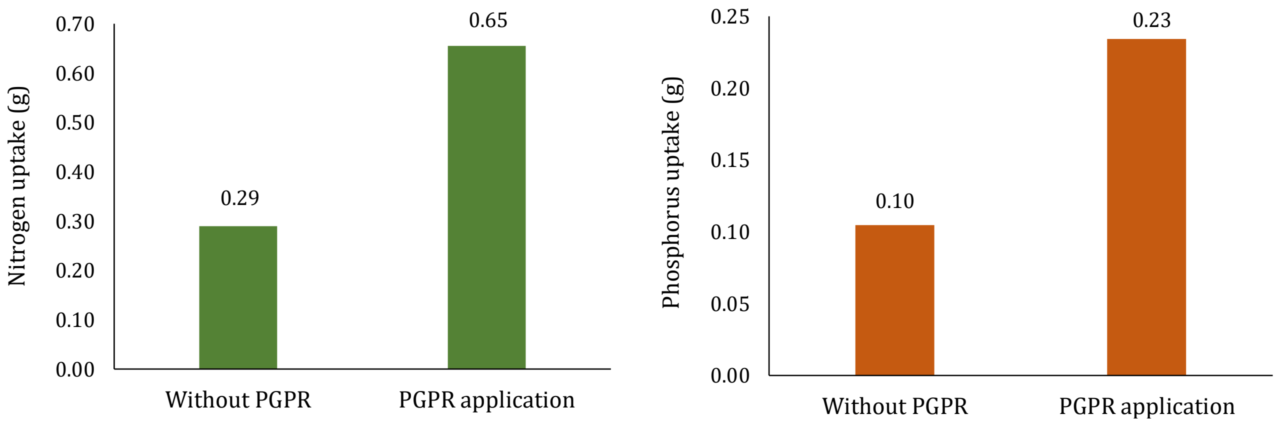

Figure 2. Nitrogen and phosphorus uptake of tomato plants under PGPR treatments.

Nitrogen-fixing bacteria in PGPR contribute to nitrogen availability through the activity of nitrogenase, thereby increasing nitrogen supply to plants. Meanwhile, phosphate-solubilizing bacteria in PGPR convert insoluble soil phosphorus into plant available forms via acidolysis, chelation, and ion-exchange reactions (Chowdhury et al., 2021; He et al., 2019). These findings are consistent with those of Ali et al. (2025) and Bariyyah (2025), who reported that PGPR significantly enhances the accessibility of essential nutrients for plants, particularly nitrogen, through nitrogen fixation and phosphate solubilization.

Relative growth rate

The relative growth rate of tomato plants under different levels of cattle manure ash, for both PGPR-treated and untreated plants, indicated that the highest average growth rate occurred during the 14–21 DAT period (Figure 3).

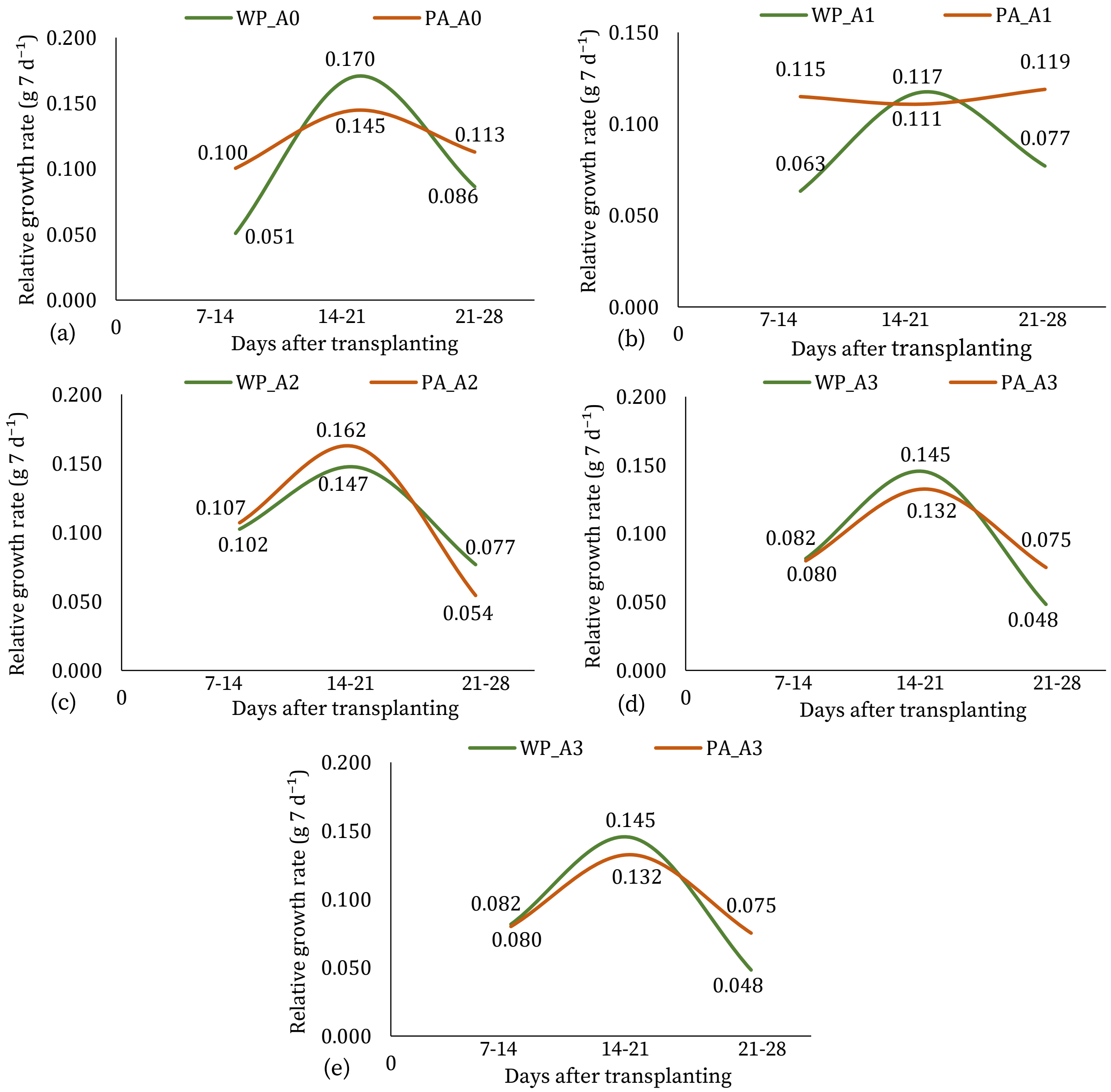

Figure 3. Relative growth rate of tomato plants with and without PGPR application with dolomite at 2.6 ton ha^{-1} a); cattle manure ash at 5 ton ha^{-1} (b); 10 ton ha^{-1} (c); 15 ton ha^{-1} (d); and 20 ton ha^{-1} (e). WP: Without PGPR; PA: PGPR application; A0: Dolomite 2.6 ton ha^{-1}; A1: Cattle manure ash 5 ton ha^{-1}; A2: Cattle manure ash 10 ton ha^{-1}; A3: Cattle manure ash 15 ton ha^{-1}; A4: Cattle manure ash 20 ton ha^{-1}; DAT: Days after transplanting.

Observations at 7–14 DAT represented the initial growth phase, while the 21–28 DAT period corresponded to the maximum vegetative phase, during which assimilate accumulation from photosynthesis begins to be redirected toward flowering and fruiting (Mahmudi et al., 2022). Photosynthetic activity significantly affects RGR through biomass accumulation, which includes all organic matter produced via photosynthesis, nutrient uptake, and water absorption, resulting from various physiological mechanisms (Zafitra et al., 2025).

During the 7-14 DAT period, PGPR application resulted in higher RGR values compared to untreated plants across all treatments, including dolomite at 2.6 ton ha^{-1} and cattle manure ash at 5-20 ton ha^{-1}. Differences in RGR between untreated and PGPR-treated plants were already evident during this early growth phase (Figure 3). In the 14-21 DAT period, PGPR-treated plants maintained higher RGR values than untreated plants. Within the cattle manure ash treatments, increasing the ash dose from 5 to 15 ton ha^{-1} corresponded with increased RGR, whereas the 20 ton ha^{-1} dose did not further enhance RGR compared to the previous dose (Figure 3). During 21-28 DAT, the differences between PGPR-treated and untreated plants remained apparent across all dolomite and cattle manure ash levels, with PGPR-treated plants consistently exhibiting higher RGR values than untreated plants (Figure 3).

Plant height

The analysis of variance indicated a significant interaction effect between PGPR application and cattle manure ash on tomato plant height. The HSD test showed that, in PGPR-treated plants, mean plant height differed among the levels of cattle manure ash. The control treatment (dolomite at 2.6 ton ha^{-1}) produced the tallest plants, which were not significantly different from those treated with cattle manure ash at 5, 10, and 15 ton ha^{-1}. However, increasing the ash dose to 20 ton ha^{-1} resulted in a decrease in plant height, which was significantly lower than the control and the 5 and 10 ton ha^{-1} treatments. In contrast, the plants without PGPR did not show significant differences in height across all ash levels and the control (Table 1).

Table 1. Average of plant height (cm), shoot dry weight (g), and root dry weight (g) under the interaction of PGPR application and cattle manure ash.

Treatments	Cattle manure ash (ton ha^{-1})					HSD 0.05
	Dolomite (2.6)	5	10	15	20	
Plant height (cm)						
Without PGPR	26.86bcd	22.73cd	25.99bcd	32.81abcd	24.27bcd	11.78
PGPR application	39.93a	34.63ab	34.30abc	29.30abcd	21.42d	
Shoot dry weight (g)						
Without PGPR	4.14bc	2.71bc	3.42bc	4.76bc	3.12bc	3.37
PGPR application	8.18a	5.93ab	4.93abc	4.05bc	2.38c	
Root dry weight (g)						
Without PGPR	1.66ab	0.89de	1.14c	1.00d	0.78e	0.13
PGPR application	1.73a	0.76e	1.66ab	1.54b	0.95d	

Note: Numbers followed by the same letter are not significantly different based on the HSD test at the 0.05 level.

The results indicate a synergistic relationship between PGPR and cattle manure ash in promoting plant height, with 5 ton ha^{-1} of ash being sufficient to replace the role of dolomite. Chemically, cattle manure ash contributes to soil pH improvement, cation exchange capacity (CEC), and increased availability of macro- and micronutrients (Doli et al., 2020; Radian et al., 2024). Biologically, PGPR acts as a biofertilizer that supports plant growth and development by enhancing the availability of nutrients such as nitrogen, which can be optimally absorbed by plants (Etesami & Maheshwari, 2018; Kalam et al., 2017; Mahdi et al., 2020; Sagar et al., 2020).

Shoot dry weight

The dry shoot weight of tomato plants was significantly effect of the interaction between PGPR application and cattle manure ash. The HSD test indicated that, in PGPR-treated plants, mean shoot dry weight differed among the levels of cattle manure ash. The control treatment (dolomite at 2.6 ton ha^{-1}) produced the highest shoot dry weight, which was significantly higher than the 15 and 20 ton ha^{-1} ash treatments, but not significantly different from the 5 and 10 ton ha^{-1} treatments. In contrast, the plants without PGPR showed no significant differences in shoot dry weight across all ash levels and the control (Table 1).

The increase in shoot dry weight observed in this study is closely related to the enhancement of tomato plant height resulting from the interaction of PGPR and cattle manure ash. Correlation analysis showed a strong positive relationship between plant height and shoot dry weight (r^2 = 0.92). This is because shoot growth directly reflects biomass accumulation from photosynthetic activity (Qu et al., 2017). Soil pH improvement by cattle manure ash, together with the role of PGPR as a biofertilizer, facilitates nutrient utilization by tomato plants by increasing the availability of nitrogen and other nutrients involved in chlorophyll synthesis and vegetative tissue development (Backer et al., 2018; Radian et al., 2024). Root dry weight

The root dry weight was significantly affected by the interaction between PGPR application and cattle manure ash. The HSD test showed that PGPR-treated plants exhibited the highest root dry weight with dolomite at 2.6 ton ha^{-1}, which was significantly higher than the 5, 15, and 20 ton ha^{-1} ash treatments, but not significantly different from the 10 ton ha^{-1} ash treatment. In untreated PGPR, the highest root dry weight was observed with dolomite at 2.6 ton ha^{-1} and was significantly higher than all cattle manure ash levels (Table 1).

The results indicate that PGPR-treated plants with 10 ton ha^{-1} cattle manure ash produced root dry weight comparable to dolomite, suggesting that the presence of PGPR can optimize the function of cattle manure ash as a soil ameliorant in supporting root growth (Magana et al., 2020). Soil chemical improvement by the ash likely creates a more favorable rhizosphere environment for PGPR activity, enabling the bacteria to enhance nutrient availability and stimulate root development through phytohormone production (Sharma et al., 2024).

Conversely, the reduction in root dry weight at 5, 15, and 20 ton ha^{-1} ash indicates that root response is highly dependent on ash dosage. Roots are more sensitive to pH changes and nutrient imbalance than shoots, so non-optimal ash application may inhibit root system development (Xia et al., 2024). In plants without PGPR, all ash treatments resulted in lower root dry weight compared to dolomite, indicating that soil chemical improvement by ash alone is insufficient to support optimal root growth without biological activity in the soil.

Number of fruits per plant

The number of tomato fruits per plant was significantly affected by the interaction between PGPR application and cattle manure ash. The HSD test showed that PGPR-treated plants with dolomite (2.6 ton ha^{-1}) produced the highest mean fruit number of 40 fruits per plant, which was significantly higher than plants treated with cattle manure ash at 5, 10, and 20 ton ha^{-1}, whereas the 15 ton ha^{-1} ash treatment did not differ significantly. In untreated plants, fruit number differed significantly between dolomite and 5 ton ha^{-1} ash, but was not significantly different from the 10, 15, and 20 ton ha^{-1} ash treatments (Table 2).

In general, PGPR-inoculated plants treated with cattle manure ash produced fewer fruits than those treated with dolomite, except at the 15 ton ha^{-1} dose, which showed comparable fruit numbers. This indicates that, at specific doses, cattle manure ash can improve soil chemical conditions suitable for supporting PGPR activity in enhancing fruit set. Furthermore, the increased fruit number in PGPR-treated plants was closely associated with higher phosphorus uptake (Figure 2) (Gashash et al., 2022).

Phosphorus plays a key role in energy transfer (ATP), flower formation, and fruit development and maturation. Thus, increased phosphorus availability and uptake enhance the physiological capacity of plants to support fruit set and retention (Rehan et al., 2023). Conversely, in plants without PGPR, cattle manure ash did not consistently increase fruit number, indicating that soil chemical improvement alone is insufficient to optimize the generative phase. Without biological soil activity, the increased nutrient availability resulting from ash application cannot be fully utilized for fruit formation, resulting in lower fruit numbers compared to PGPR-treated plants (Zhang et al., 2024).

Table 2. Average number of fruits per plant and fruit weight per plant (g) under the interaction of PGPR application and cattle manure ash.

Treatments	Cattle manure ash (ton ha^{-1})					HSD 0.05
	Dolomite (2.6)	5	10	15	20	
Number of fruits per plant						
Without PGPR	29.17bc	16.00d	27.33bc	24.33bcd	18.83cd	10.40
PGPR application	40.50a	20.67bcd	29.67b	30.50ab	28.83 bc	
Fruit weight per plant (g)						
Without PGPR	1043.36b	425.15d	913.12b	827.10bc	517.44cd	373.08
PGPR application	1513.18a	973.74b	1067.50b	1028.17b	717.70bcd	

Note: Numbers followed by the same letter are not significantly different based on the HSD test at the 0.05 level.

Fruit weight per plant

The fruit weight per plant was significantly influenced by the interaction between PGPR application and cattle manure ash. The HSD test showed the highest fruit weight per plant occurred in the interaction between PGPR and dolomite (2.6 ton ha^{-1}), with a mean of 1,513.18 g, which was significantly higher than all levels of cattle manure ash. In contrast, untreated plants without PGPR showed no significant differences in fruit weight across all ash levels and the control (dolomite) (Table 2). The fruit weight results corresponded with the fruit number, as both PGPR and dolomite treatments produced the highest fruit number and weight.

The high fruit weight observed under PGPR and dolomite treatments indicates that more optimal soil chemical conditions, particularly soil pH and base cation balance, play a crucial role in enhancing PGPR effectiveness during the generative phase. A more neutral soil reaction can increase phosphorus availability, which is essential for fruit formation and enlargement, as soil pH is a major factor regulating nutrient availability and uptake by plants (Penn & Camberato, 2019). A stable rhizosphere environment allows PGPR to improve nutrient uptake efficiency, contributing to photosynthate synthesis and its translocation to generative organs. PGPR are known to enhance phosphorus availability and uptake through phosphate solubilization mechanisms (Yang et al., 2024). Although cattle manure ash has the potential to improve soil chemical properties, the results of this study indicate that, at all ash levels tested, fruit weight per plant remained lower than in the dolomite treatment when combined with PGPR, suggesting that pH regulation by dolomite provides more favorable conditions for nutrient uptake efficiency and higher crop yield (Penn & Camberato, 2019).

Conclusions

PGPR application significantly enhanced the physiological responses of tomato plants grown in Ultisol, as indicated by increased nitrogen uptake (0.65 g per plant), phosphorus uptake (0.23 g per plant), and a higher relative growth rate. PGPR improved plant growth at cattle manure ash doses up to 5 ton ha^{-1}, achieving plant height and shoot dry weight comparable to the dolomite treatment. Root dry weight, however, exhibited an optimal response at 10 ton ha^{-1} ash. In terms of yield, PGPR increased fruit number at 15 ton ha^{-1} ash, with results equivalent to the dolomite treatment. Nevertheless, fruit weight per plant under cattle manure ash combined with PGPR did not fully reach the levels observed with dolomite, although the 5 ton ha^{-1} ash dose produced higher fruit weight than in plants without PGPR application. These findings indicate that cattle manure ash can partially replace dolomite in tomato cultivation, can increase vegetative growth at 5 ton ha^{-1} and certain yield components at higher rates of 10 ton ha^{-1}.

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