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Optimization of Liquid Biofertilizer Concentrations for Improving Tomato (*Solanum lycopersicum* L.) Productivity under Reduced Nitrogen Input in Oxisols

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Abstract
Background: Oxisols are highly weathered soils with low fertility and limited nutrient availability, which restrict crop productivity. Improving nutrient efficiency through biological inputs is an important strategy to maintain crop yield while reducing dependence on synthetic fertilizers. **Aim:** This study aimed to evaluate the effects of different concentrations of liquid biofertilizer on tomato growth, yield, and selected soil chemical properties under reduced nitrogen fertilization in Oxisols. **Methods:** The experiment was conducted at the Experimental Garden of the Faculty of Agriculture, Muhammadiyah University of Jakarta, from December 2023 to March 2024 using a Randomized Block Design. Five treatments were applied, consisting of full nitrogen fertilization without biofertilizer and 70% nitrogen fertilization combined with liquid biofertilizer at concentrations of 2, 4, 6, and 8 mL L^{-1}. Plant growth, yield, and selected soil chemical properties were evaluated. **Results:** The application of liquid biofertilizer affected soil chemical properties and tomato productivity under reduced nitrogen input. The 4 mL L^{-1} treatment produced the highest fruit weight of 354.80 g $plant^{-1}$, equivalent to 22.17 tons ha^{-1}, indicating improved nitrogen use efficiency and crop performance. **Conclusion:** Optimizing liquid biofertilizer concentration can enhance tomato productivity while reducing nitrogen fertilizer requirements in Oxisols. This approach provides a potential strategy for sustainable crop production by improving nutrient efficiency and minimizing environmental impacts associated with excessive nitrogen application.

Keywords: crop productivity; nutrient efficiency; soil fertility; sustainable agriculture; tomato cultivation

1. Introduction

Tomato (*Solanum lycopersicum* L.) is one of the economically important horticultural crops widely cultivated worldwide. According to FAOSTAT (2024), global tomato production reached approximately 192 million tons in 2023, highlighting its importance as one of the major vegetable crops in terms of production volume and economic value. The increasing demand for tomatoes as fresh produce and raw material for food processing industries highlights the importance of improving tomato productivity through efficient and sustainable crop management practices. Besides serving as a source of vitamins, minerals, and antioxidants, tomato has broad market potential for both fresh consumption and processing industries. The increasing market demand requires continuous improvement in tomato productivity through appropriate crop management practices, particularly nutrient management. Among essential plant nutrients, nitrogen (N) plays a crucial role in determining tomato growth and productivity.

Nitrogen is an essential macronutrient involved in chlorophyll formation, amino acid and protein synthesis, and the regulation of vegetative growth and photosynthetic activity, which ultimately determine biomass accumulation and crop yield. Adequate nitrogen availability enhances chlorophyll content and photosynthetic efficiency, whereas nitrogen deficiency can induce chlorosis and reduce photosynthetic capacity (Juhaeti et al., 2024; Pangaribuan et al., 2022). Nitrogen availability is also positively associated with leaf development, plant vigor, and biomass production, which contribute to improved fruit formation and yield in tomato plants (Khairi et al., 2023). Therefore, effective nitrogen management is a key factor in achieving sustainable tomato production.

However, nitrogen management remains a major challenge in low-fertility soils such as Oxisols. Oxisols are highly weathered tropical soils characterized by low pH, low organic matter content, limited nutrient retention capacity, and high concentrations of iron (Fe) and aluminum (Al) oxides. These characteristics restrict nutrient availability and reduce soil fertility, thereby limiting crop productivity. Nitrogen applied through inorganic fertilizers in Oxisols is often lost through leaching, volatilization, and microbial immobilization, reducing fertilizer effectiveness and increasing environmental risks (Sanchez, 2019). Moreover, excessive nitrogen application does not always result in proportional increases in crop yield and may contribute to nitrate contamination and greenhouse gas emissions (Rawichandran et al., 2024). Therefore, developing efficient and environmentally sustainable nutrient management strategies is essential, particularly for crop production on marginal soils.

One promising approach is the use of liquid biofertilizers containing functional microorganisms that improve soil biological activity and nutrient availability. Beneficial microorganisms in biofertilizers can enhance nutrient cycling, accelerate organic matter decomposition, and facilitate the transformation of nutrients into forms more accessible to plants (Bhattacharyya & Jha, 2012). Several microbial genera, such as Azotobacter and Azospirillum, have been reported to contribute to biological nitrogen fixation and to promote plant growth by improving nutrient availability and producing growth-promoting substances (Golla, 2019). The use of these microorganisms has the potential to enhance crop productivity, particularly under nutrient-limited conditions, such as those found in Oxisols.

Although previous studies have demonstrated the beneficial effects of biofertilizers on horticultural crops, information regarding the effectiveness of liquid biofertilizers in improving crop productivity under reduced nitrogen input in low-fertility soils remains limited. In particular, the optimal concentration of liquid biofertilizer combined with reduced nitrogen fertilization for tomato cultivation in Oxisols has not been widely reported. Therefore, this study aimed to evaluate the effects of different concentrations of liquid biofertilizer on soil chemical properties, growth, and productivity of tomato plants under reduced nitrogen fertilization in Oxisols. The novelty of this research lies in determining the optimal concentration of liquid biofertilizer that maintains or improves tomato productivity while reducing inorganic nitrogen inputs. This approach is expected to contribute to the development of more efficient and sustainable fertilization strategies for horticultural crop production on marginal soils. Previous studies have mainly focused on the general benefits of biofertilizers for crop growth and soil improvement. However, limited information is available regarding the appropriate concentration of liquid biofertilizer that can maintain tomato productivity while reducing nitrogen fertilizer inputs, particularly in Oxisols with low nutrient retention capacity.

2. Methods

2.1 Place and Time

The experiment was conducted from December 2023 to March 2024 at the Experimental Garden of the Faculty of Agriculture, Muhammadiyah University of Jakarta, Indonesia. The experimental site was located at an altitude of approximately 25 m above sea level, with Oxisols as the dominant soil type. Soil chemical analyses were conducted at PT. Bumi Ventila Indonesia, Bogor, Indonesia.

2.2 Research Design and Data Analysis

The experiment was arranged using a Randomized Block Design (RBD) with five treatments and five replications, yielding 25 experimental units. Each experimental unit consisted of three tomato plants, resulting in a total of 75 plants. The experiment was conducted to evaluate the effects of different concentrations of liquid biofertilizer, combined with reduced nitrogen input, on tomato growth, soil chemical properties, and productivity under Oxisol conditions.

The treatments consisted of a full nitrogen fertilizer application as the control and reduced nitrogen fertilizer combined with different concentrations of liquid biofertilizer. The control treatment (P0) received the recommended nitrogen fertilizer rate without liquid biofertilizer application. The P1, P2, P3, and P4 treatments received 70% of the recommended nitrogen fertilizer dosage (0.94 g urea plant^{-1}) combined with liquid biofertilizer concentrations of 2, 4, 6, and 8 mL L^{-1}, respectively. Phosphorus and potassium fertilizers were applied at the full recommended rates in all treatments to maintain balanced nutrient availability. The liquid biofertilizer used in this study contained functional microorganisms that support nutrient cycling and plant growth. The application concentrations were evaluated to determine the optimal level of liquid biofertilizer to maintain or improve tomato productivity under reduced nitrogen fertilization.

The collected data were analyzed using analysis of variance (ANOVA) to determine the effects of treatments. When significant differences were detected among treatments, mean comparisons were performed using the Honestly Significant Difference (HSD) test at a 5% significance level.

2.3 Plant Cultivation and Experimental Management

The growing medium consisted of Oxisol soil mixed with goat manure at a 1:1 (v/v) ratio. The mixture was placed in polybags measuring 40 × 40 cm, each containing 10 kg of growing medium, and incubated for one week before planting. Tomato seeds of the Servo F1 variety were germinated in seed trays containing a mixture of soil, goat manure, and rice husk charcoal at a 1:1:1 (v/v/v) ratio. Seedlings aged 14 days, with 4–5 fully expanded leaves, were transplanted into polybags at a rate of 1 plant per polybag.

Plant maintenance included irrigation twice daily, manual weed removal, installation of plant supports at one week after transplanting, and mechanical pest and disease control. When pest and disease incidence increased, deltamethrin insecticide (2 mL L^{-1}) and mancozeb fungicide (2 g L^{-1}) were applied. Fruit harvesting was conducted at 67 days after transplanting when fruits reached physiological maturity.

2.4 Fertilizer and Liquid Biofertilizer Application

Inorganic fertilizers were applied three times during the growing period, namely at planting, 3 weeks after transplanting (WAT), and 5 WAT using the placement method around the plant root zone. The control treatment (P0) received the full recommended fertilizer dosage consisting of 1.34 g urea plant^{-1}, 3 g SP-36 plant^{-1}, and 0.66 g KCl plant^{-1} according to Rokhminarsi et al. (2022). Treatments P1–P4 received 70% nitrogen fertilizer (0.94 g urea plant^{-1}), while phosphorus and potassium fertilizers were maintained at the full recommended dosage. Liquid biofertilizer was applied three times at 2, 4, and 6 WAT through soil drenching around the root zone. The application volumes were 100, 150, and 200 mL plant^{-1}, respectively. Biofertilizer application was conducted in the afternoon to maintain microbial viability and activity.

2.5 Soil Chemical Analysis

Soil samples were collected before and after the treatment application to evaluate changes in soil chemical properties. The analyzed soil parameters included soil pH, total nitrogen (N-total), available phosphorus (P-available), exchangeable potassium (K-available), and soil organic carbon (C-organic). Soil pH was measured using a pH meter, total nitrogen was determined using the Kjeldahl method, available phosphorus was analyzed using the Bray I extraction method, exchangeable potassium was determined using NH_4OAc extraction, and organic carbon content was analyzed using the Walkley–Black method.

2.6 Plant Growth, Generative Phase, and Yield Measurements

Plant observations were conducted to evaluate the effects of applying liquid biofertilizer on tomato growth, reproductive development, and productivity under reduced nitrogen inputs. Vegetative growth parameters included plant height, number of branches, and number of leaves. Plant height was measured with a ruler, while the number of branches and leaves was recorded weekly from 2 weeks after transplanting until the flowering stage. Generative parameters included days to first flowering and days to first harvest. The flowering period was determined by the number of days from transplanting to the appearance of the first flower, while the first harvest period was recorded when fruits reached physiological maturity. In each experimental unit, all three tomato plants were observed and measured, and the average value was used as the representative value for each treatment unit.

Yield components were measured during harvesting, including the number of fruits per plant, fruit diameter, fruit length, and fruit weight per plant. Fruit diameter and length were measured using a digital caliper, while fruit weight was determined using a digital balance. Tomato productivity was calculated by converting fruit weight per plant into tons per hectare based on plant population density. Productivity was calculated using the following equation:

$$\text{Productivity (ton ha}^{-1}\text{)} = \text{fruit weight per plant} \times \text{plant population per hectare.}$$

The plant population was determined based on the planting distance applied during cultivation.

3. Results and Discussion

3.1 Changes in Soil Chemical Properties of Oxisols

The application of liquid biofertilizer at different concentrations significantly affected several chemical properties of Oxisols, including soil pH, total nitrogen, available phosphorus, exchangeable potassium, and organic carbon content (Table 1).

The application of liquid biofertilizer increased soil pH compared with the control treatment. Soil pH increased from 4.46 in the control treatment to 4.98 at the 6 mL L^{-1} biofertilizer concentration. This improvement indicates that microbial activity in the liquid biofertilizer contributed to changes in soil chemical conditions through organic matter transformation and the production of microbial metabolites. The decomposition of organic substrates and the formation of humic compounds may increase soil buffering capacity and reduce the activity of exchangeable H^+ ions, thereby improving soil acidity (Sobari et al., 2023). However, soil pH slightly decreased at the highest biofertilizer concentration (8 mL L^{-1}), reaching 4.81. This response suggests that the effect of microbial application on soil pH was nonlinear, possibly due to differences in microbial activity, organic acid production, and nutrient transformation at higher microbial inputs (Hapsoh et al., 2021). Furthermore, the high content of Fe and Al oxides characteristic of Oxisols may influence pH dynamics through interactions with organic compounds and nutrient retention mechanisms (Ganestri et al., 2021).

Table 1. Response of Oxisols chemical properties to different concentrations of liquid biofertilizer

Liquid Biofertilizer Concentration	Soil pH	Total N (%)	Available P (ppm)	Exchangeable K (cmol(+) kg^{-1})	Organic C (%)
0 mL L^{-1}	4.46 d	0.13 cd	4.56 a	0.11 a	1.13 d
2 mL L^{-1}	4.69 c	0.12 d	3.33 b	0.10 b	1.80 c
4 mL L^{-1}	4.80 b	0.14 bc	2.97 c	0.07 c	2.29 b
6 mL L^{-1}	4.98 a	0.15 ab	1.96 d	0.09 b	3.01 a
8 mL L^{-1}	4.81 b	0.16 a	2.99 c	0.09 b	2.27 b

Note: Values followed by the same letter within the same column are not significantly different according to the Honestly Significant Difference (HSD) test at a 5% significance level.

Total nitrogen content showed an increasing trend with increasing liquid biofertilizer concentration. The highest total nitrogen content was observed in the 8 mL L^{-1} treatment (0.16%), compared with 0.13% in the control treatment. The increase in soil nitrogen availability may be associated with enhanced microbial activity, including biological nitrogen fixation and organic matter mineralization processes. Functional microorganisms in biofertilizers can contribute to nitrogen transformation by converting organic nitrogen into mineral forms more available for plant uptake (Soumaré et al., 2020; Ramakrishnan et al., 2023). Nevertheless, the increase in total nitrogen was relatively limited, which may be related to the low organic matter content of Oxisols and the strong interactions between nitrogen compounds and Fe-Al oxide surfaces, which influence nitrogen dynamics in highly weathered soils (Zuluaga et al., 2024; Aal et al., 2023).

In contrast, available phosphorus showed a decreasing trend following liquid biofertilizer application. The highest available phosphorus content was observed in the control treatment (4.56 ppm), while the lowest value occurred at 6 mL L^{-1} (1.96 ppm). The reduction in available phosphorus following biofertilizer application may indicate increased utilization of phosphorus by microorganisms and plants during biological activity. In highly weathered soils such as Oxisols, phosphorus availability is also strongly controlled by adsorption processes involving Fe and Al oxides, which can reduce the amount of soluble phosphorus available in the soil solution (Firmansyah et al., 2016). Therefore, the decrease in available phosphorus does not necessarily indicate reduced availability of phosphorus for plants but may reflect increased biological immobilization and nutrient cycling within the soil system.

Exchangeable potassium content also decreased after biofertilizer application, from 0.11 cmol(+) kg^{-1} in the control treatment to 0.07 cmol(+) kg^{-1} at the 4 mL L^{-1} concentration. This reduction may be associated with increased potassium uptake by plants and microorganisms during growth and nutrient cycling processes. In addition, the low nutrient retention capacity of Oxisols, due to their low cation exchange capacity, may contribute to potassium mobility and potential losses through leaching (Ginting, 2020). The changes in exchangeable potassium indicate that microbial activity influenced nutrient dynamics in the soil–plant system.

Soil organic carbon showed the most pronounced response to the application of liquid biofertilizer. Organic carbon content increased from 1.13% in the control treatment to 3.01% at the 6 mL L^{-1} concentration. This increase indicates that liquid biofertilizer stimulated microbial processes involved in organic matter decomposition and humification. Microbial transformation of organic substrates can promote the formation of more stable humic compounds, thereby increasing soil organic carbon accumulation (Boguta et al., 2021). The improvement in soil organic carbon is particularly important in Oxisols because organic matter plays a key role in enhancing soil fertility, nutrient retention capacity, and microbial activity.

Overall, the application of liquid biofertilizer improved several chemical characteristics of Oxisols, particularly soil pH, total nitrogen, and organic carbon content. The greatest improvement in soil chemical properties was generally observed at the 6 mL L^{-1} concentration, although some parameters responded differently depending on nutrient dynamics and microbial interactions. These findings indicate that liquid biofertilizer has potential as a complementary input to improve soil quality under reduced nitrogen fertilization in Oxisols.

3.2 Vegetative Growth of Tomato Plants

The application of liquid biofertilizer at different concentrations significantly affected tomato vegetative growth, particularly plant height, while the number of branches and leaves showed no significant differences among treatments (Table 2). The reduced plant height at higher biofertilizer concentrations may be associated with changes in assimilate allocation and plant growth regulation. Under certain conditions, increased microbial activity can modify nutrient availability and rhizosphere interactions, resulting in greater investment in leaf development and reproductive potential rather than stem elongation. This indicates that plant height alone may not represent overall plant performance.

Table 2. Effect of liquid biofertilizer concentrations on tomato vegetative growth

Liquid Biofertilizer Concentration	Plant Height (cm)	Number of Branches (branches $plant^{-1}$)	Number of Leaves (leaves $plant^{-1}$)
0 mL L^{-1}	96.13 b	23.73a	92.00a
2 mL L^{-1}	87.73 ab	26.60a	104.53a
4 mL L^{-1}	87.53 ab	25.33a	102.87a
6 mL L^{-1}	86.13 ab	25.43a	113.83a
8 mL L^{-1}	80.73 a	23.93a	110.13a

Note: Values followed by the same letter within the same column are not significantly different according to the Honestly Significant Difference (HSD) test at a 5% significance level.

The application of liquid biofertilizer at different concentrations significantly affected tomato vegetative growth, particularly plant height, while the number of branches and leaves showed no significant differences among treatments (Table 2). The control treatment (0 mL L^{-1}) produced the highest plant height (96.13 cm), which was significantly higher than the 8 mL L^{-1} treatment (80.73 cm). This result indicates that increasing the concentration of liquid biofertilizer did not directly promote tomato stem elongation under the experimental conditions. The plant height response showed a non-linear pattern, suggesting that interactions among microbial activity, nutrient availability, and plant physiological responses influenced vegetative growth.

The lower plant height observed at higher biofertilizer concentrations may be related to differences in nutrient allocation patterns. Plant growth is not only determined by nutrient availability but also by the balance between vegetative organs, environmental conditions, and microbial interactions in the rhizosphere. A higher concentration of microbial inoculants may increase microbial activity in the growing medium; however, excessive microbial populations may temporarily alter nutrient dynamics through competition for available nutrients during microbial proliferation (Kumar et al., 2021). In addition, under Oxisols conditions with low nutrient retention capacity, nutrient availability may fluctuate depending on microbial transformation processes and plant uptake dynamics.

Although plant height decreased at higher biofertilizer concentrations, the application of liquid biofertilizer tended to improve other vegetative characteristics, particularly leaf development. The number of branches ranged from 23.73 to 26.60 branches plant^{-1} and did not differ significantly among treatments. The highest branch number was recorded in the 2 mL L^{-1} treatment (26.60 branches plant^{-1}), indicating that moderate biofertilizer concentration may provide favorable conditions for lateral growth. Beneficial microorganisms contained in biofertilizers can contribute to nutrient cycling, organic matter decomposition, and the production of plant growth-promoting compounds that support vegetative development (Paturohman et al., 2017).

The number of leaves also showed no significant differences among treatments; however, numerical improvements were observed in biofertilizer-treated plants. The highest number of leaves was recorded in the 6 mL L^{-1} treatment (113.83 leaves plant^{-1}), followed by the 8 mL L^{-1} treatment (110.13 leaves plant^{-1}), compared with only 92.00 leaves plant^{-1} in the control treatment. The increased leaf formation at moderate to high biofertilizer concentrations suggests that liquid biofertilizer may enhance nutrient availability and rhizosphere activity, particularly through enhanced nitrogen transformation. Nitrogen availability plays an important role in leaf expansion and chlorophyll formation, while beneficial microorganisms may also produce growth-promoting substances such as auxins and cytokinins that stimulate cell division and tissue development (Akhtar et al., 2020). However, because microbial populations and phytohormone production were not directly measured in this study, these mechanisms should be considered as possible explanations for the observed responses.

The contrasting responses of plant height and leaf development indicate that the application of liquid biofertilizer influenced tomato growth patterns rather than uniformly increasing all vegetative parameters. The control treatment supported greater vertical growth, whereas biofertilizer applications, particularly at 6 mL L^{-1}, promoted greater leaf formation. A higher number of leaves may increase photosynthetic surface area and support assimilate production for reproductive growth and fruit development. Therefore, the effectiveness of liquid biofertilizer in Oxisols should be evaluated based on overall plant performance, including yield components, rather than plant height alone.

3.3 Generative Phase and Yield Components of Tomato Plants

The application of liquid biofertilizer at different concentrations (0–8 mL L^{-1}) did not significantly affect the generative phase and yield components of tomato plants (Table 3). Parameters including days to flowering, days to first harvest, number of fruits, fruit diameter, and fruit length showed relatively similar responses among treatments. These results indicate that the application of liquid biofertilizer under the experimental conditions did not directly affect the reproductive development of tomato plants, although it influenced several vegetative growth parameters.

The flowering time ranged from 32.07 to 33.00 days after transplanting (DAT), while the first harvest occurred between 69.63 and 70.80 DAT. The absence of significant differences among treatments suggests that the application of liquid biofertilizer did not substantially accelerate or delay tomato reproductive development. Flower initiation and fruit maturation are complex physiological processes regulated by genetic characteristics, environmental conditions, and the availability of essential nutrients. Therefore, changes in soil microbial activity may not immediately translate into differences in flowering and harvesting time.

Table 3. Effect of liquid biofertilizer concentrations on generative phase and yield components of tomato plants

Liquid Biofertilizer Concentration	Days to Flowering (DAT)	Days to First Harvest (DAT)	Number of Fruits (fruit plant^{-1})	Fruit Diameter (cm)	Fruit Length (cm)
0 mL L^{-1}	32.78a	70.80a	8.20a	4.55a	5.15a
2 mL L^{-1}	33.00a	70.33a	8.37a	4.60a	5.05a
4 mL L^{-1}	32.07a	69.73a	8.33a	4.47a	5.19a
6 mL L^{-1}	32.37a	70.57a	7.77a	4.25a	5.02a
8 mL L^{-1}	32.47a	69.63a	8.47a	4.40a	4.97a

Note: Values followed by the same letter within the same column are not significantly different according to the Honestly Significant Difference (HSD) test at a 5% significance level.

The yield components also showed similar responses among treatments. The number of fruits ranged from 7.77 to 8.47 fruits plant^{-1}, with the highest numerical value observed in the 8 mL L^{-1} treatment (8.47 fruits plant^{-1}). Fruit diameter ranged from 4.25 to 4.60 cm, while fruit length ranged from 4.97 to 5.19 cm. Although these differences were not statistically significant, the observed variation suggests that the application of liquid biofertilizer may have influenced nutrient dynamics and plant physiological processes to some extent.

Fruit development is highly dependent on the balance between photosynthetic assimilation and nutrient availability, particularly nitrogen (N), phosphorus (P), and potassium (K). Nitrogen supports chlorophyll formation and vegetative development, while phosphorus and potassium play important roles in flowering, fruit formation, carbohydrate translocation, and fruit quality. When nutrient availability is not sufficiently increased, improvements in vegetative growth may not necessarily result in significant increases in fruit size or yield components (Rahayu et al., 2022). Fruit development is also determined by the allocation of photosynthates from source organs, mainly leaves, toward reproductive organs as sink tissues. Therefore, increased vegetative growth does not always correspond to increased fruit size when assimilate distribution remains limited (Safriansyah et al., 2022).

The results also suggest that the effect of liquid biofertilizer may depend on the balance between vegetative and reproductive growth. Biofertilizer microorganisms can enhance nutrient cycling and improve rhizosphere conditions, thereby supporting leaf development and plant biomass accumulation. However, converting these improvements into reproductive yield requires adequate nutrient availability and efficient allocation of assimilates during the reproductive stage. Similar findings have been reported: biofertilizer responses are often concentration-dependent and may vary with plant developmental stages and environmental conditions (Lee & Ryu, 2021).

The characteristics of Oxisols may also explain the limited response of yield components. Oxisols generally have low nutrient retention capacity, high Fe and Al oxide content, and strong phosphorus fixation properties, which may restrict nutrient availability during critical reproductive stages. Under such conditions, microbial activity alone may not be sufficient to significantly increase fruit development without additional improvements in nutrient supply and soil fertility conditions (Farrasati et al., 2021).

Overall, liquid biofertilizer application at concentrations of 0–8 mL L^{-1} did not significantly affect the generative phase or yield components of tomato plants. However, the numerical increase in fruit number at higher biofertilizer concentrations suggests that microbial-based fertilization may support plant productivity. The results indicate that liquid biofertilizer functions primarily as a soil biological enhancer, while maximizing tomato yield under Oxisols conditions requires integration with balanced nutrient management, particularly during the reproductive phase.

3.4 Fruit Weight and Tomato Productivity

The application of liquid biofertilizer at different concentrations significantly affected fruit weight and tomato productivity (Table 4). The 4 mL L^{-1} treatment produced the highest fruit weight, reaching 354.80 g $plant^{-1}$, with a productivity of 22.17 tons ha^{-1}. This treatment was significantly higher than the 6 and 8 mL L^{-1} treatments, while the control (0 mL L^{-1}) and 2 mL L^{-1} treatments showed similar responses. These results indicate that tomato plants responded optimally to a specific concentration of the liquid biofertilizer rather than showing a linear response to increasing biofertilizer application rates.

Table 4. Effect of liquid biofertilizer concentrations on fruit weight and tomato productivity

Liquid Biofertilizer Concentration	Fruit Weight (g $plant^{-1}$)	Productivity (ton ha^{-1})
0 mL L^{-1}	334.47ab	20.90ab
2 mL L^{-1}	333.27ab	20.82ab
4 mL L^{-1}	354.80a	22.17a
6 mL L^{-1}	300.97b	18.81b
8 mL L^{-1}	306.47b	19.15b

Note: Values followed by the same letter within the same column are not significantly different according to the Honestly Significant Difference (HSD) test at a 5% significance level.

The highest fruit weight and ProductivityProductivity observed at 4 mL L^{-1} suggest that this concentration provided a favorable balance between microbial activity, nutrient availability, and plant physiological requirements during fruit development. Fruit production is strongly influenced by the availability of assimilates produced during photosynthesis and the ability of plants to allocate these assimilates toward reproductive organs. Adequate nutrient availability, particularly nitrogen (N), phosphorus (P), and potassium (K), plays an important role in supporting fruit formation, enlargement, and dry matter accumulation. The productivity obtained in this study (18.81–22.17 tons ha^{-1}) is within the range commonly reported for tomato production under suboptimal soil conditions, although direct comparisons depend on cultivar, climate, nutrient management, and cultivation system. The result indicates that liquid biofertilizer application may help maintain competitive productivity under reduced nitrogen input.

Liquid biofertilizer may improve plant productivity through biological processes that enhance nutrient cycling, including nitrogen transformation, phosphate solubilization, and nutrient mobilization by functional microorganisms (Backer et al., 2018; Rahmayuni et al., 2025). Beneficial microorganisms, including plant growth-promoting bacteria (PGPB), may also improve rhizosphere conditions and support root development by producing growth-promoting compounds and enhancing nutrient availability (Anwar et al., 2021). These processes may increase plant capacity to acquire nutrients and support photosynthetic activity, resulting in greater assimilation production for fruit filling.

The improvement in productivity at the 4 mL L^{-1} concentration is also related to the balance between vegetative and reproductive growth. Although the 6 mL L^{-1} treatment produced a higher number of leaves during the vegetative stage, this did not translate into higher fruit yield. In contrast, the 4 mL L^{-1} treatment appeared to provide a more favorable balance between vegetative development and assimilate allocation toward fruit formation. This indicates that greater vegetative growth does not always correspond to increased ProductivityProductivity when nutrient distribution and reproductive sink capacity are limiting.

Nitrogen contributes to chlorophyll synthesis and photosynthetic capacity; phosphorus plays an important role in energy transfer and reproductive development; and potassium regulates enzyme activation, water balance, and the translocation of carbohydrates toward fruit tissues (Wulansari et al., 2022). The interaction among these nutrients determines the success of fruit development and filling, as reflected in fruit weight and overall Productivity.

In contrast, the lower fruit weight and ProductivityProductivity observed at 6 and 8 mL L^{-1} indicate that increasing liquid biofertilizer concentration beyond the optimum level did not provide additional benefits. This response suggests that excessive biofertilizer application may not always improve plant performance due to possible changes in microbial interactions, nutrient dynamics, or competition within the rhizosphere. Therefore, the effectiveness of biofertilizer depends not only on the presence of beneficial microorganisms but also on achieving an appropriate concentration that matches plant nutrient requirements and soil conditions.

The characteristics of Oxisols may also influence tomato plants' response to biofertilizer application. The low nutrient-retention capacity and strong nutrient-fixation properties of Oxisols can limit nutrient availability during fruit development. Under these conditions, liquid biofertilizer serves as a complementary input that supports soil biological processes, but optimal crop productivity still requires balanced nutrient management.

Overall, the results demonstrate that a liquid biofertilizer concentration of 4 mL L^{-1} was the most effective treatment for improving tomato fruit weight and ProductivityProductivity under reduced nitrogen input in Oxisols. This finding highlights the importance of optimizing biofertilizer concentration, as both insufficient and excessive applications may reduce its effectiveness in supporting tomato yield production.

4. Limitations and Future Directions

This study was conducted during one growing season and evaluated only one tomato cultivar under specific Oxisol conditions. Therefore, further validation across different soil types, climatic conditions, and tomato cultivars is required. Future studies should investigate microbial dynamics, nitrogen-use efficiency, and the economic feasibility of liquid biofertilizer application.

5. Conclusion

The application of liquid biofertilizer improved several chemical properties of Oxisols, particularly soil pH, total nitrogen, and organic carbon content, with the most pronounced improvement observed at the 6 mL L^{-1} concentration. However, most vegetative growth and generative parameters of tomato plants were not significantly affected by liquid biofertilizer application. The 4 mL L^{-1} treatment resulted in the highest fruit weight and productivity, reaching 354.80 g $plant^{-1}$ and 22.17 tons ha^{-1}, respectively. Under the specific experimental conditions of this study, including the tested tomato cultivar, growing period, and Oxisol conditions, the 4 mL L^{-1} liquid biofertilizer treatment showed the best performance in maintaining tomato productivity while reducing nitrogen input. Further evaluation across different soil types, climatic conditions, tomato cultivars, and longer cultivation periods is required before broader recommendations can be established. These findings indicate that liquid biofertilizer has potential as a complementary input to support sustainable nutrient management in low-fertility soils.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

ChatGPT was used as an AI-assisted tool to support language refinement, grammar checking, and the improvement of the clarity and readability of scientific writing. The use of this tool was limited to assisting with manuscript preparation and did not involve generating original research ideas, experimental design, data collection, data analysis, or the interpretation of research findings. After using this tool, the authors carefully reviewed, revised, and verified all content to ensure the manuscript's accuracy, scientific integrity, and originality. The authors take full responsibility for the content and conclusions presented in this publication.

Authorship Contribution Statement

Welly Herman contributed to conceptualization, methodology development, supervision, validation, formal analysis, manuscript review, and editing. **Restu Setyaji Putra** contributed to experimental implementation, field investigation, data collection, laboratory analysis, data curation, and preparation of the initial manuscript draft. **Erlina Rahmayuni** contributed to conceptualization, research design, data interpretation, formal analysis, literature review, and manuscript preparation and refinement. All authors reviewed and approved the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests, personal relationships, or affiliations that could have appeared to influence the work reported in this paper.

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References

Aal, A., Assiri, M., AL-Farga, A., Moustafa, Y., Hammam, A., Haddad, S.,& Abdelkarim, N. (2023). Exploration of the Benefits of biofertilizers for attaining food security in egypt's agriculture. *Agronomy*, *13*(10), 2477. https://doi.org/10.3390/agronomy13102477

Akhtar, S., Mekureyaw, M., Pandey, C., & Roitsch, T. (2020). Role of cytokinins for interactions of plants with microbial pathogens and pest insects. *Frontiers in Plant Science, 10*. https://doi.org/10.3389/fpls.2019.01777

Anwar, H., Wang, X., Hussain, A., Rafay, M., Ahmad, M., Latif, M., & Mustafa, A. (2021).

Comparative effects of bio-wastes in combination with plant growth-promoting bacteria on growth and productivity of okra. *Agronomy, 11*(10), 2065. https://doi.org/10.3390/agronomy11102065

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 commercialization. Frontiers in Plant Science, 9, 1473. https://doi.org/10.3389/fpls.2018.01473

Bhattacharyya, P. N., & Jha, D. K. (2012). Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. *World Journal of Microbiology and Biotechnology, 28*, 1327–1350.

Boguta, P., Skic, K., Sokołowska, Z., Frąc, M., & Sas-Paszt, L. (2021). Chemical transformation of humic acid molecules under the influence of mineral, fungal and bacterial fertilization in the context of the agricultural use of degraded soils. *Molecules, 26*(16), 4921. https://doi.org/10.3390/molecules26164921

Farrasati, R., Pradiko, I., Rahutomo, S., & Ginting, E. (2021). Review: pemupukan melalui tanah serta daun dan kemungkinan mekanismenya pada tanaman kelapa sawit. *Warta Pusat Penelitian Kelapa Sawit, 26*(1), 7-19. https://doi.org/10.22302/iopri.war.warta.v26i1.41

Firmansyah, I., Lukman, L., Khaririyatun, N., & Yufdy, M. (2016). Pertumbuhan dan hasil bawang merah dengan aplikasi pupuk organik dan pupuk hayati pada tanah alluvial. *Jurnal Hortikultura, 25*(2), 133-141.

Food and Agriculture Organization of the United Nations. (2024). *Agricultural production statistics 2010–2023*. FAOSTAT. https://www.fao.org/faostat/

Ganestri, R., Winarso, S., & Asyiah, I. (2021). Efektivitas pupuk organik dan pupuk hayati cair terhadap pemulihan tanah terdegradasi di Desa Sucopangepok. *Jurnal Tanah dan Iklim, 45*(2), 175–185. https://doi.org/10.21082/jti.v45n2.2021.175-185

Ginting, E. (2024). Pupuk kimia, pupuk organik, atau pupuk hayati ? Memahami filosofi pemupukan untuk perkebunan kelapa sawit yang berkelanjutan. *Warta Pusat Penelitian Kelapa Sawit, 29*(3), 147-160. https://doi.org/10.22302/iopri.war.warta.v29i3.159

Golla, A. (2019). Soil acidity and its management options in Ethiopia: A Review. *International Journal of Scientific Research and Management, 7*(11). https://doi.org/10.18535/ijsrm/v7i11.em01

Hapsoh, Dini, I., Salbiah, D., & Syahputra, R. (2021). The growth of oil palm seeds (*Elaeis guineensis* Jacq.) at main nursery through giving biofertilizers consortium of cellulolytic bacteria. *Asian Journal of Applied Sciences, 9*(1). https://doi.org/10.24203/ajas.v9i1.6506

Juhaeti, T., Hidayati, N., Setyowati, N., Wawo, A., & Widiyono, W. (2024). The performances of adlay (*Coix lacryma-jobi* L.) as component of agroforestry on teak (*Tectona grandis* L.f.) plantation. *Tropical Life Sciences Research, 35*(2), 87-106. https://doi.org/10.21315/tlsr2024.35.2.5

Khairi, A., Jayaputra, J., & Tejowulan, S. (2023). Combination of bio-organo-mineral fertilizers on optimizing the growth and production of tomatoes (*Solanum lycopersicum* L.) in dryland environment. *Jurnal Ilmiah Pertanian, 20*(2). https://doi.org/10.31849/jip.v20i2.10901

Kumar, M., Giri, V., Pandey, S., Gupta, A., Patel, M., Bajpai, A., & Siddique, K. (2021). Plant-growth-promoting rhizobacteria emerging as an effective bioinoculant to improve the growth, production, and stress tolerance of vegetable crops. *International Journal of Molecular Sciences, 22*(22), 12245. https://doi.org/10.3390/ijms222212245

Lee, S. and Ryu, C. (2021). Algae as new kids in the beneficial plant microbiome. *Frontiers in*

Plant Science, 12. https://doi.org/10.3389/fpls.2021.599742

Pangaribuan, D., Ermawati, E., Suryani, N., & Maria, W. (2022). The growth and yield responses of two bean cultivars to organic and inorganic nitrogen sources. Biodiversitas *Journal of Biological Diversity, 23*(3). https://doi.org/10.13057/biodiv/d230359

Paturohman, E., Surahman, M., Setiawan, A., & Giyanto, G. (2017). Efektivitas mikrob probiotik dalam formulasi pasta dan cair terhadap mutu benih dan pertumbuhan jagung hibrida. *Jurnal Penelitian Pertanian Tanaman Pangan, 1(*3), 211. https://doi.org/10.21082/jpptp.v1n3.2017.p211-221

Rahayu, R., Hodiyah, I., & Natawijaya, D. (2022). Pengaruh urine sapi dan rpt tterhadap pertumbuhan dan hasil mentimun jepang (*Cucumis sativus* L. Var. Roberto 92). *Media Pertanian, 7*(1), 34-47. https://doi.org/10.37058/mp.v7i1.4790

Rahmayuni, E., Syadiyah, T. H., & Herman, W. (2025). Pengaruh kombinasi pupuk anorganik (n, p, k) dan pupuk kascing terhadap terung ungu. *Cemara, 22*(2), 111–123. https://doi.org/https://doi.org/10.24929/fp.v22i2.4794

Ramakrishnan, B., Maddela, N., Venkateswarlu, K., & Megharaj, M. (2023). Potential of microalgae and cyanobacteria to improve soil health and agricultural productivity: a critical view. *Environmental Science Advances, 2*(4), 586-611. https://doi.org/10.1039/d2va00158f

Rawichandran, D., Kasim, S., Zuan, A., Effendi, M., & Raguraj, S. (2024). Utilization of yeasts in promoting plant growth in acidic soil – A review. *Agrivita Journal of Agricultural Science, 46*(1), 196. https://doi.org/10.17503/agrivita.v46i1.4241

Rokhminarsi, E., P. Hidayat., A. Febriani dan N. W. A. Leana. 2022. Pengaruh pemberian pupuk mikoriza trichoderma dan dosis pengurangan pupuk anorganik terhadap pertumbuhan dan hasil tanaman tomat (*Lycopersicum esculentum* L.). *Agronomika: Jurnal Budidaya Pertanian Berkelanjutan. 21*(2): 10-18.

Sanchez, P. A. (2019). *Properties and management of soils in the tropics*. Cambridge University Press.

Sobari, I., Sasmita, K., Rokhmah, D., Sakiroh, S., & Supriadi, H. (2023). Respons pertumbuhan bibit kopi arabika dan sifat kimia media tanam terhadap pemberian pupuk hayati dan pupuk organik. *Jurnal Agro, 10*(2), 252-266. https://doi.org/10.15575/27343

Soumaré, A., Diédhiou, A., Thuita, M., Hafidi, M., Ouhdouch, Y., Gopalakrishnan, S., & Kouisni, L. (2020). Exploiting Biological Nitrogen Fixation: A Route Towards a Sustainable Agriculture. *Plants, 9*(8), 1011. https://doi.org/10.3390/plants9081011

Safriansyah, G., Zulfita, D., & Hariyanti, A. (2022). Respon Pertumbuhan dan hasil beberapa varietas jagung manis dengan pemberian pupuk hayati pada lahan gambut. *Jurnal Sains Pertanian Equator, 12*(1), 85. https://doi.org/10.26418/jspe.v12i1.60349

Wulansari, R., Maryono, M., Darmawan, D., Athallah, F., & Hakim, F. (2022). Bio-organo mineral effect on soil fertility, nutrient uptake, and sweet corn (*Zea mays* L. saccharata) growth planted in inceptisols soils. *Indonesian Mining Journal, 25*(1), 49-58. https://doi.org/10.30556/imj.vol25.no1.2022.1282

Zuluaga, M., Fattorini, R., Cesco, S., & Pii, Y. (2024). Plant-microbe interactions in the rhizosphere for smarter and more sustainable crop fertilization: the case of PGPR-based biofertilizers. *Frontiers in Microbiology, 15*. https://doi.org/10.3389/fmicb.2024.1440978