JPPIPA 11(11) (2025)

Jurnal Penelitian Pendidikan IPA

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Effects of Biofertilizer Application and Organic Matter Incubation on Soil Chemical Properties

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Received: September 19, 2025
Revised: October 10, 2025
Accepted: December 02, 2025
Published: December 02, 2025

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DOI: 10.29303/jppipa.v11i11.13342

Abstract: Soil organic matter is essential for maintaining soil fertility and supporting sustainable agricultural production. However, raw organic matter does not directly enhance soil chemical properties without a sufficient decomposition period. This study evaluated the effects of organic matter incubation and biofertilizer concentrations on soil chemical characteristics. The experiment was conducted from June to August 2024 in the Greenhouse Laboratory of Gunadarma Technopark University, Jamali Village, West Java, using a completely randomized factorial design. Treatments consisted of four biofertilizer concentrations (0, 10, 15, and 20 mL/L) and five incubation periods of cow manure (0, 1, 2, 3, and 4 weeks), each replicated four times, resulting in 80 experimental units. The results showed a significant interaction between incubation duration and biofertilizer concentration on soil pH, organic carbon, total nitrogen, C/N ratio, available phosphorus (P_2O_5), and available potassium (K_2O). The four-week incubation combined with 10–20 mL/L of biofertilizer produced the most notable improvements, increasing pH to neutral levels, raising organic carbon and nitrogen contents, achieving an optimal C/N ratio, and enhancing P availability, although K remained low. These findings indicate that combining biofertilizer application with an adequate incubation period effectively improves soil fertility and offers a viable strategy for long-term soil management and agricultural productivity.

Keywords: Biofertilizer; Incubation period; Organic matter; Soil fertility; Sustainable agriculture

Introduction

Soil is fundamental to sustainable agriculture and global food production, yet intensive farming has led to declining soil quality, threatening long-term productivity (Hossain, 2021). Organic matter enhances soil quality by supplying nutrients, improving structure, and regulating nutrient cycling through microbial decomposition (Ma et al., 2023; Tong, 2024). It also increases water and nutrient retention while stabilizing soil aggregates, preventing erosion (X. Li et al., 2023). However, decomposition requires time and optimal conditions, delaying the immediate benefits of organic fertilization (Arfarita et al., 2020). Biofertilizers significantly enhance microbial diversity and activity, particularly dehydrogenase enzymes, which drive organic matter oxidation and overall soil biological processes (Da Cunha Leme Filho et al., 2024; Guan, 2023; Shi et al., 2023). However, excessive organic inputs may reduce microbial diversity and enzyme function, compromising soil health (Ye et al., 2020). Long-term organic fertilizer application improves soil nutrient concentrations and microbial activity, supporting sustained soil health and plant growth (R. Wang et al., 2021; Wu et al., 2020).

How to Cite:
Aisyah, Asnur, P., Fitrianingsih, & Risnawati. (2025). Effects of Biofertilizer Application and Organic Matter Incubation on Soil Chemical Properties. *Jurnal Penelitian Pendidikan IPA*, *11*(11), 386–397. https://doi.org/10.29303/jppipa.v11i11.13342

Organic matter plays a crucial role in soil fertility and the sustainability of agricultural production. Soils with high organic matter content exhibit enhanced structure, aeration, water retention capacity, and nutrient storage, all of which are essential for optimal plant growth (J. Li et al., 2015). Humus, the final product of organic matter decomposition, significantly improves the soil's ability to retain water and nutrients, particularly in regions with erratic rainfall patterns (B. Wang et al., 2020). The decomposition process involves fragmentation, mineralization, and humification, enabling organic matter to maximize soil benefits, enhance crop yields, and reduce reliance on chemical fertilizers (Wan et al., 2021; Wen et al., 2020). However, despite these advantages, organic matter application is often suboptimal due to insufficient microbial activity and inadequate incubation periods.

To maximize the benefits of organic matter, an incubation process is necessary, allowing microorganisms to proliferate and metabolize organic compounds into C-organic fractions, facilitating mineralization and the release of essential nutrients such as nitrogen, phosphorus, and sulfur, along with trace micronutrients (Cui et al., 2018; Salma et al., 2018). This process enhances nutrient availability for plant uptake, improving soil fertility and productivity (Siregar et al., 2017). The duration of the incubation period determines the maturity of organic matter, while biofertilizer application accelerates the decomposition process, ensuring that nutrients become readily available for plant absorption. Moreover, the incubation process involves integrating organic matter into the soil to modify its pH and structure, necessitating a specific waiting period before land use, which varies based on soil type and environmental conditions (Aisyah et al., 2018).

Soil quality is profoundly affected by climate change and unsustainable agricultural practices, necessitating improved organic matter management to enhance sustainability and food security. The incubation of organic matter is a key method because it helps microbes grow and breaks down organic matter into C-organic compounds through mineralization. This releases nutrients like nitrogen, phosphorus, sulfur, and micronutrients (Patriani et al., 2022; Qaswar et al., 2020). Research indicates that combining organic materials with chemical fertilizers is more effective in increasing soil nutrient concentrations than using chemical fertilizers alone, as it enhances nutrient availability and soil fertility (Chen et al., 2022; He et al., 2024). Longer incubation times affect how well organic matter improves the chemical properties of soil because they control how much organic matter breaks down and nutrients are released (J. Li et al., 2015). However, limited research has explored the specific effects of the incubation period of organic materials combined with biofertilizers on soil chemical properties, highlighting a knowledge gap in sustainable soil management (He et al., 2024).

The application of organic fertilizers has been shown to enhance microbial diversity and activity, which play a vital role in nutrient cycling and soil health improvement (Kuziemska et al., 2020; Xu et al., 2022). Additionally, integrating organic materials with biofertilizers improves the capacity of soil to exchange cations and retain moisture, further supporting plant growth and overall soil productivity (Guo et al., 2023). Understanding the interactions between organic matter incubation and biofertilizer application is critical for optimizing strategies for managing soil fertility. So, the point of this study is to look into how the incubation period of organic materials at different biofertilizer concentrations changes the chemical properties of the soil. Specifically, it examines key soil parameters, including pH, organic carbon, total nitrogen, the C/N ratio, available phosphorus, and available potassium, to provide insights into sustainable soil fertility management.

Method

Soil Sampling and Experimental Design

Soil sampling was conducted at a depth of 0–15 cm in the Universitas Gunadarma Technopark, which had remained fallow for a decade. The samples were placed in 10 kg polybags for experimental treatments. To improve soil fertility, farmyard manure was applied at 10 tons per hectare. The experiment followed a completely randomized factorial design with two factors: biofertilizer application rate and incubation period.

Biofertilizer Treatments and Incubation Procedure

Four biofertilizer treatments were applied: (1) control (H0, no biofertilizer), (2) 10 mL/L (H1), (3) 15 mL/L (H2), and (4) 20 mL/L (H3). The biofertilizer was uniformly mixed with soil and cattle manure. Soil moisture was maintained at field capacity using distilled water to sustain microbial activity. The experiment involved 80 polybags arranged in a randomized factorial design ($4 \times 5 \times 4 = 80$). Incubation periods were set at 0 (M0), 1 (M1), 2 (M2), 3 (M3), and 4 weeks (M4), conducted under ambient laboratory conditions at ~30°C.

Soil Sample Collection and Analytical Procedures

At each incubation period, soil samples were systematically collected from all treatments. Undisturbed samples were analyzed for aggregate stability, while disturbed samples were used for physicochemical analysis. Composite samples were air-dried, sieved, and subjected to chemical characterization. Measured parameters included pH (using a calibrated pH meter), moisture content, C/N ratio, available phosphorus (P_2O_5) via Bray I extraction, and available potassium (K_2O) via ammonium acetate extraction. All analyses followed standardized soil testing protocols to ensure accuracy and reliability.

Result and Discussion

Soil pH

Soil pH regulates nutrient solubility and microbial activity, directly impacting plant growth. Optimal pH enhances nutrient uptake and supports beneficial microbes. Higher pH improves macronutrient availability but reduces micronutrient solubility. ANOVA results confirmed that biofertilizer application with 1–4 weeks of incubation significantly influenced soil pH, while non-treated soils showed no significant changes (Table 1).

A significant interaction was seen between applying biofertilizer (10 mL/L for two weeks) and the changes in soil pH. After four weeks, the highest pH (7.36, neutral) was found at 10–20 mL/L. Biofertilizers stimulate decomposer bacteria, accelerating organic matter mineralization. The rise in pH is linked to organic acid production, which chelates aluminum (Al), reducing acidity. These findings align with Hamed et al. (2014) on organic matter–mineralization correlations and Tan (2010) on soil amelioration. Biofertilizer management that works well improves soil fertility, microbial activity, and long-term use of nutrients (Daniel, 2022; Fitriatin et al., 2021; Kaur, 2024).

Table 1. Interaction between biofertilizer application and incubation period on the average soil pH (H_2O) of the planting medium.

Incubation Period (weeks)				Biofertilizer (ml/L)
	0 m//L (H0)	10 ml/L (H1)	15 ml/L (H2)	20 ml/L (H3)
Without Incubation (M0)	5.01 a	5.03 b	5.03 b	5.03 b
Incubation 1 week (M1)	5.02 a	5.06 b	5.06 c	5.06 c
Incubation 2 week (M2)	5.02 a	5.06 c	5.06 c	5.06 c
Incubation 3 week (M3)	5.02 a b	5.40 d	5.40 d	5.41 d
Incubation 4 week (M4)	5.02 a b	7.36 e	7.36 e	7.36 e

Note: Numbers followed by different letters in rows and columns indicate significant differences based on the DMRT test at the 5% significance level.

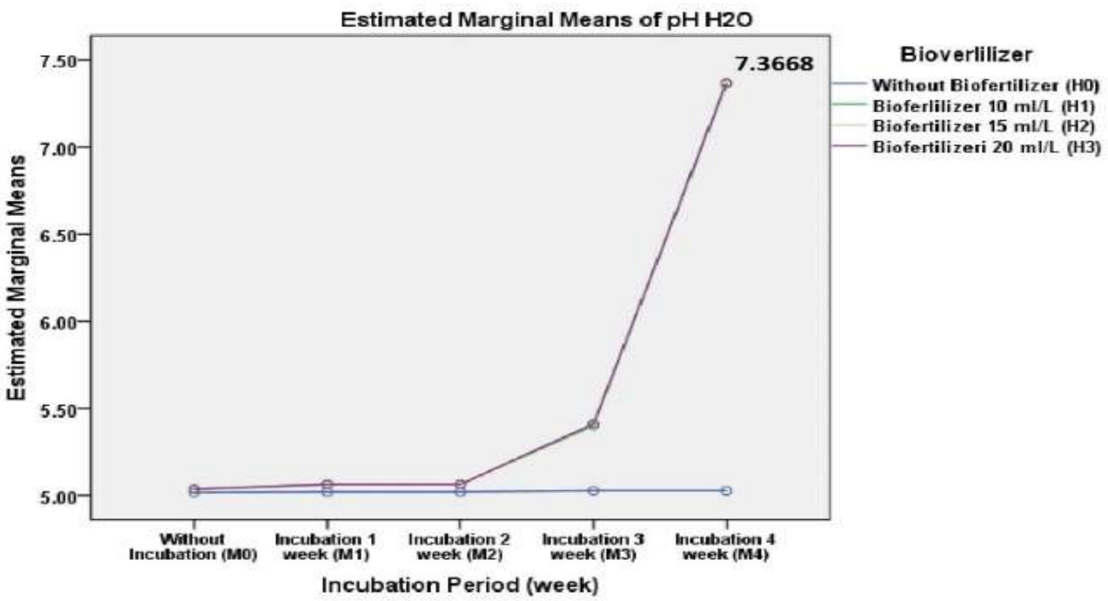

Figure 1. Interaction between biofertilizer treatment and incubation period on the average pH of the planting medium

Figure 1 illustrates the interaction between biofertilizer treatment and incubation period on soil pH. In the absence of biofertilizer, soil pH remained stable with no significant changes. Conversely, biofertilizer application led to a notable pH increase from the second week onward, with higher concentrations producing a more pronounced effect. After four weeks, the highest pH value (7.3668, neutral range) was seen at a biofertilizer concentration of 20 mL/L (H3). This shows that biofertilizer works to raise soil pH over time.

Organic Carbon (C-organic)

The incubation of organic matter accelerates decomposition, transforming complex compounds into stable forms, with biofertilizers playing a crucial role in this process. Biofertilizers add beneficial microorganisms that boost microbial activity and raise the amount of C-organic matter in the planting medium (Debska, 2016). The amount of biofertilizer applied and incubation duration significantly affect organic carbon content, influencing soil fertility and quality. Table 2 illustrates these effects, demonstrating how biofertilizer treatments and incubation periods modify soil organic matter composition. Understanding these interactions is vital for optimizing soil management and promoting sustainable agriculture.

Table 2. Shows how adding biofertilizer and letting it sit for a while affects the average amount of C-organic matter in the planting medium.

Incubation Period (weeks)	Biofertilizer (ml/L)			
	0 m//L (H0)	10 ml/L (H1)	15 ml/L (H2)	20 ml/L (H3)
Without Incubation (M0)	0.20 a	0.21 a	0.21 a	0.21 a
Incubation 1 week (M1)	0.20 a	0.22 a	0.22 a	0.22 a
Incubation 2 week (M2)	0.21 a	0.22 a	0.30 b	0.22 a
Incubation 3 week (M3)	0.21 a	2.99 b	3.00 c	3.00 b
Incubation 4 week (M4)	0.21 a	4.66 c	4.96 d	5.00 d

Note: Numbers followed by different letters in rows and columns indicate significant differences based on the DMRT test at the 5% significance level.

The findings of this study demonstrate that the interaction between biofertilizer concentration and incubation duration exerts a significant influence on the accumulation of organic carbon (C-organic) in the planting medium. In the absence of an incubation period, the application of biofertilizer did not result in a substantial increase in C-organic content. However, a notable enhancement was observed from the third to the fourth week of incubation, particularly at a biofertilizer concentration of 10 mL/L, which yielded the highest average C-organic content of 4.6667. This pattern is consistent with the stabilization of soil pH within the neutral range, indicating that an optimal pH environment facilitates the retention and accumulation of soil organic carbon.

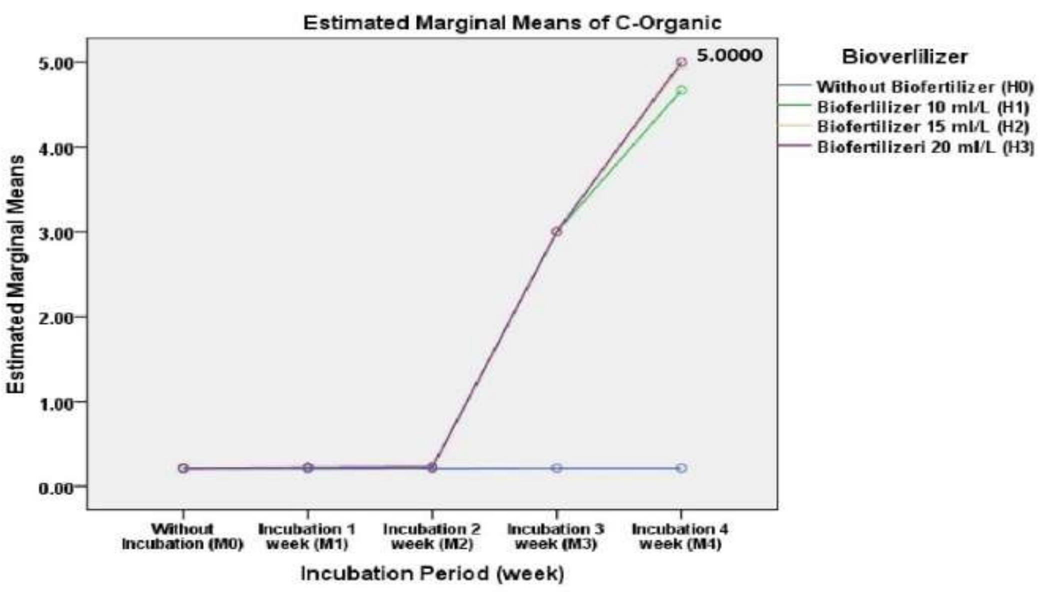

Figure 2. Interaction of biofertilizer treatment and incubation period on the average C-Organic content of the planting medium

Figure 2 presents the interaction between biofertilizer concentration and incubation duration in relation to C-organic content, emphasizing the role of microbial activity in accelerating the decomposition and mineralization of organic matter over time. Overall, these findings indicate that the incubation period has a significant effect on soil organic carbon content. A longer incubation duration allows for greater decomposition of organic matter, leading to an increased accumulation of organic carbon. This decomposition process is driven by enhanced microbial activity over time, resulting in more stable and plant-available organic carbon. Extending the incubation period can improve the quality of the growing medium and support better plant growth (Harsani et al., 2023; Husni et al., 2022).

Total Nitrogen (N Total)

Total nitrogen (N total) is crucial for plant growth, particularly in protein and chlorophyll synthesis, and is influenced by microbial decomposition during organic matter incubation (Saputri et al., 2021). Cattle manure decomposition accelerates nitrogen release, enhancing plant uptake (Indriana et al., 2021). Experimental results showed significant nitrogen variations across biofertilizer treatments and incubation periods. The highest levels were recorded at 20 mL/L without incubation (H3M0, 0.1166%) and after three weeks without biofertilizer (H0M3, 0.1067%). Notably, the nitrogen content rose sharply after three weeks of using 10 mL/L biofertilizer (H1M3, 0.8132%), reaching 0.8400% after four weeks. This shows that the microbes were better at mineralizing nitrogen.

Table 3. Shows how adding biofertilizer and letting it sit for a while affects the total nitrogen content of the planting medium on average.

Incubation Period (weeks)	Biofertilizer (ml/L)			
	0 m//L (H0)	10 ml/L (H1)	15 ml/L (H2)	20 ml/L (H3)
Without Incubation (M0)	0.08 a	0.08 a	0.08 a	0.11 b
Incubation 1 week (M1)	0.09 a	0.11 b	0.11 b	0.13 a
Incubation 2 week (M2)	0.10 a	0.80 c	0.80 c	0.80 c
Incubation 3 week (M3)	0.10 b	0.81 c	0.81 c	0.81 c
Incubation 4 week (M4)	0.10 b	0.84 d	0.84 d	0.84 d

Note: *Numbers followed by different letters in rows and columns indicate significant differences based on the DMRT test at the 5% significance level.*

Figure 3 illustrates the interaction effects of biofertilizer concentration and incubation period on the average total nitrogen (N) content in the planting medium. The significant interaction between treatments is reflected in the highest total N values observed with biofertilizer applications at concentrations of 10 to 20 mL/L over the incubation period. This interaction plays a crucial role in enhancing the effectiveness of biofertilizer application. These findings align with the organic matter mineralization process, during which nitrogen, phosphorus, and sulfur are released in substantial quantities, along with smaller amounts of micronutrients (Dikinya & Mufwanzala, 2010).

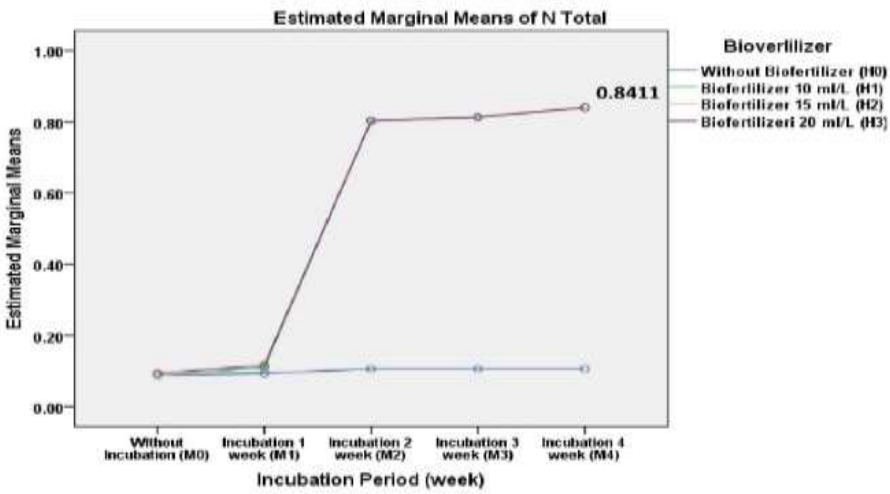

Figure 3. Interaction graph of biofertilizer treatment and incubation period on total N of planting media

C/N ratio

The C/N ratio is a key determinant of organic matter decomposition, influencing nutrient release and soil fertility. It regulates microbial activity, affecting nitrogen mineralization and humus formation, making it a critical indicator of soil quality (Haibin et al., 2001). The study findings (Table 4) reveal a significant interaction between biofertilizer application and incubation duration, impacting the C/N ratio. This interaction enhances microbial activity, accelerates nitrogen mineralization, and optimizes nutrient availability for plant growth.

Table 4. Interaction between biofertilizer application and incubation period on the average C-organic content in the planting media.

Incubation Period (weeks)				Biofertlizer (ml/L)
	0 m//L (H0)	10 ml/L (H1)	15 ml/L (H2)	20 ml/L (H3)
Without Incubation (M0)	3.09 a	3.10 a	3.11 a	3.11 a
Incubation 1 week (M1)	3.09 a	3.13 a	3.14 a	3.14 a
Incubation 2 week (M2)	3.09 a	3.19 a	3.20 a	3.20 a
Incubation 3 week (M3)	3.09 a	3.20 a	3.20 a	3.21 a
Incubation 4 week (M4)	3.13 a	11.66 b	11.73 b	12.00 b

Note: Numbers followed by different letters in rows and columns indicate significant differences based on the DMRT test at the 5% significance level.

The C/N ratio is a sensitive indicator of soil quality, where a low ratio (C/N < 10) accelerates organic matter decomposition but may lead to nitrogen unavailability for plants, while a high ratio (C/N > 12) slows decomposition and reduces microbial activity (Haibin et al., 2001). As shown in Table 4, the average C/N ratio without biofertilizer application was very low (3.097–3.137), indicating an imbalance between carbon and nitrogen that hinders nitrogen availability. In contrast, the optimal C/N ratio for planting media ranges from 10 to 12 (Sanchez, 2019). The results demonstrate a significant interaction between biofertilizer application (10–20 mL/L) and a 4-week incubation period, leading to an ideal C/N ratio (11–12), which supports nutrient balance and enhances microbial activity.

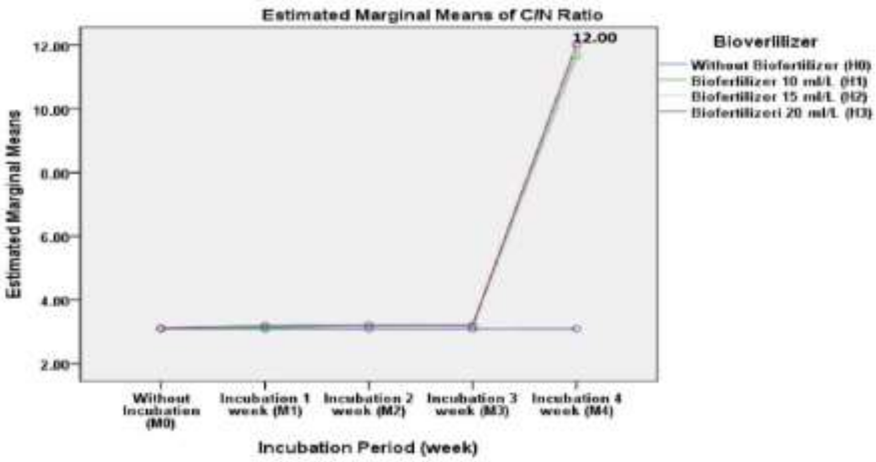

Figure 4. Graph illustrating the interaction between biofertilizer treatment and incubation period on the average C/N ratio of the planting media.

The relationship between the incubation period and the C/N ratio is shown in Figure 4. Treatments with biofertilizer at 10–20 mL/L for 3–4 weeks led to a significant rise in the ratio. When biofertilizer is added to manure, it helps break down organic matter by giving microbes more nitrogen. This speeds up the breakdown of carbon and keeps the C/N ratio normal. A study found that using 10 mL/L of biofertilizer (H1M4) for four weeks raised the average C/N ratio from 3.097 (very low) to 11.667 (moderate).

Available P

Available phosphorus (P) refers to the fraction of phosphorus in the soil that is readily accessible for plant uptake and utilization. The incorporation of biofertilizers during incubation introduces inoculants that enhance the soil P cycle by solubilizing both organic and mineral-bound phosphorus. Phosphate-solubilizing microorganisms contribute to this process through multiple mechanisms, including the dissolution of P-containing minerals via soil acidification, the release of metal-chelating compounds (primarily organic acid anions), and the enzymatic degradation of organic phosphorus compounds (Jones & Oburger, 2010). Soil pH plays a crucial role in determining P availability (Table 5).

Table 5. Illustrates the interaction between biofertilizer concentration and incubation duration in influencing the average available P content in the planting medium.

Incubation Period (week)	Biovertilizer (ml/L)			
	0 m//L (H0)	10 ml/L (H1)	15 ml/L (H2)	20 ml/L (H3)
Without Incubation (M0)	14.30 a	14.33 a	14.34 a	14.35 a
Incubation 1 week (M1)	14.32 a	14.35 a	14.36 a	14.36 a
Incubation 2 week (M2)	14.32 a	14.41 a	14.44 a	14.53 a
Incubation 3 week (M3)	14.32 a	14.54 a	14.55 a	14.64 a
Incubation 4 week (M4)	14,32 a	35.06 b	36.36 c	36.37 c

Note: Numbers followed by different letters in rows and columns indicate significant differences based on the DMRT test at the 5% significance level.

Table 5 highlights the significant impact of organic fertilizer and incubation duration on available phosphorus (P) content. Without biofertilizer, available P remains low (14.3033 mg/kg). A slight increase is observed at 10 mL/L, though still in the low range. A substantial rise occurs at 15 mL/L after four weeks, reaching 36.3667 mg/kg, classified as high. This trend aligns with Muktamar & Lifia (2020), who reported increasing P availability over 3–7 weeks. The positive correlation between pH and available P (r = 0.9891) supports findings by Manoj et al. (2020), who reported r = 0.6466.

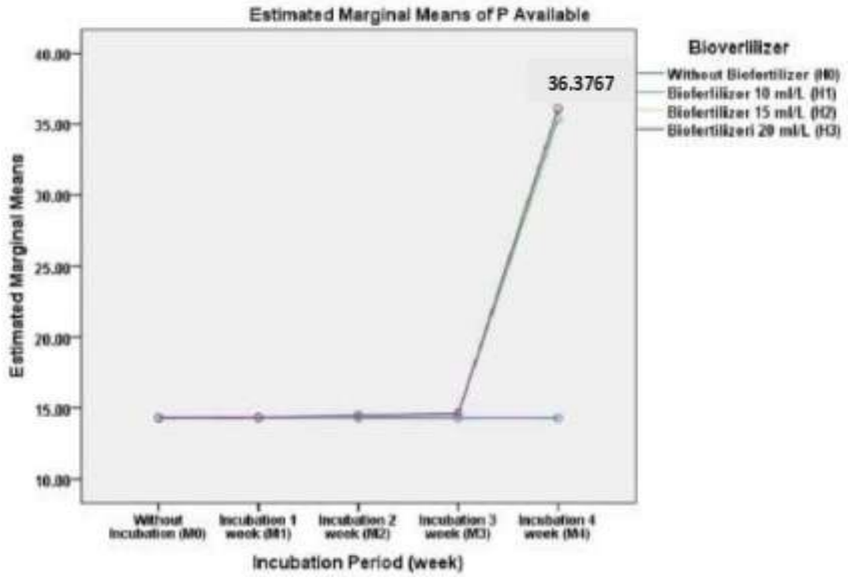

Figure 5. Interaction graph of biofertilizer treatment and incubation period on the available P value of planting media

Available K

Potassium (K) is a vital macronutrient that significantly influences plant growth, physiological processes, and overall crop productivity. Its bioavailability in soil is governed by multiple factors, including fertilizer composition, incubation duration, and soil physicochemical properties. As shown in Table 6, a significant interaction was observed between biofertilizer concentration and incubation period, with notable increases in available K at biofertilizer concentrations of 10–20 ml/L across all incubation stages.

Table 6. shows how the amount of biofertilizer and the time it is incubated affect the amount of K that is available in planting medium (me/100 g).

Incubation Period (week)	Biofertolizer (ml/L)			
	0 m//L (H0)	10 ml/L (H1)	15 ml/L (H2)	20 ml/L (H3)
Without Incubation (M0)	1.0333 a	1.0367 a	1.0367 a	1.0367 a
Incubation 1 week (M1)	1.0367 a	6.6733 b	6.6633 b	6.6833 b
Incubation 2 week (M2)	1.0433 a	6.7067 c	6.7167 c	6.7467 c
Incubation 3 week (M3)	1.0467 a	6.7900 d	6.7900 d	6.8033 d
Incubation 4 week (M4)	1.0468 a	6.8633 e	6.8700 e	6.8733 e

Note: Numbers followed by different letters in rows and columns indicate significant differences based on the DMRT test at the 5% significance level.

Table 6 demonstrates a significant effect of all treatments on potassium (K) availability, except for those without biofertilizer application. The availability of K is regulated by multiple factors, including soil mineral composition, organic matter content, pH, and cation exchange capacity (CEC) (Thomas & Hipp, 1968). Although biofertilizer application at concentrations of 10–20 mL/L with incubation periods of 1–4 weeks exhibited a notable interaction, the overall levels of available K remained low. A slight increase in available K was observed in week 4 with biofertilizer application at 10–20 mL/L, indicating a delayed response to organic matter mineralization and microbial activity. As shown in Figure 6, available K continued to rise up to week 4 under biofertilizer treatments; however, the persistently low K levels suggest that soil properties, particularly CEC and mineral composition, play a more dominant role in K retention and availability (Cui et al., 2018).

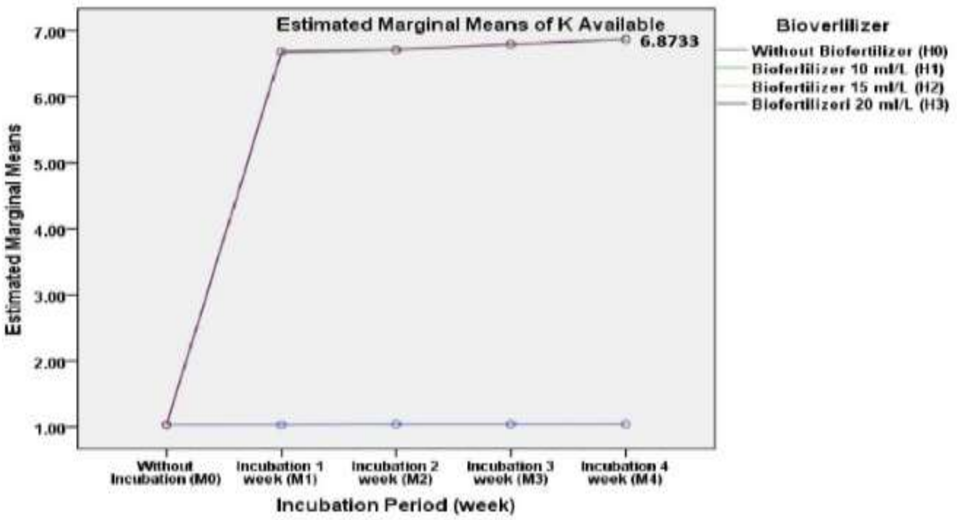

Figure 6. Interaction graph of biofertilizer treatment and incubation period on the average value of available K in planting media

Figure 6 illustrates that the treatment interaction significantly influenced the average available K. The application of biofertilizer at concentrations of 10–20 ml/L across all incubation periods led to an increase in available K; however, the levels remained very low up to the fourth week of incubation (H3M4). Despite this increase, biofertilizer application was insufficient to stabilize K availability at moderate to high levels. This limitation is likely due to the inherently low potential K content in the soil, measured at 1.04 mg/100 g, and a low cation exchange capacity (CEC) of 24.42 cmol(+)/kg, as indicated by the initial routine laboratory analysis of the planting medium.

Correlation Coefficient between pH (H2O) and P available

The relationship between pH and available phosphorus (P) shows how acidity in the soil affects the amount of P that is available. This relationship is controlled by mineralization rates and soil chemistry (Corbett, 2022). Factors such as soil type, organic matter, and cation presence (Ca, Mg) affect this relationship. Organic amendments, particularly cattle manure and biofertilizers, enhance soil pH during incubation, increasing P availability. In contrast, inorganic P sources have minimal impact and may contribute to acidification (Opala et al., 2012).

Table 7. Correlation coefficient between soil pH (H_2O) and available P.

		pH H_2O	P Available
pH H_2O	Pearson Correlation	1	0.98
	Sig. (2-tailed)		0.00
	N	60	60
P Available	Pearson Correlation	0.98	1
	Sig. (2-tailed)	0.00	
	N	60	60

Correlation is significant at the 0.01 level (2-tailed).

The correlation between soil pH (H_2O) and available phosphorus (P) in Table 7 is highly significant and strong, as indicated by a correlation coefficient of 0.989, which is close to +1. The positive sign denotes a direct relationship, meaning that an increase in soil pH (H_2O) is accompanied by a corresponding rise in available P, with a proportional increase of 98%.

Conclusion

Adding biofertilizer and letting organic matter, like cow manure, sit for a while has been shown to improve soil pH, organic carbon (C-organic), total nitrogen (N), the C/N ratio, available phosphorus (P), and available potassium (K). The results of this study show that adding 10–20 ml/L of biofertilizer to soil for four weeks raises the p Application of biofertilizer at 10–20 ml/L, combined with organic matter like cow manure, significantly improves soil chemical properties. After four weeks, soil pH increased from slightly acidic to neutral (highest at 7.36 for 20 ml/L), organic carbon reached 5%, and total nitrogen was 0.84%, indicating effective organic matter mineralization and nutrient availability. The optimal C/N ratio of 11–12 at 20 ml/L suggests balanced decomposition, while available phosphorus reached a very high category, enhancing nutrient accessibility for plants. However, available potassium did not reach optimal levels, indicating a need for additional management strategies. These results suggest that integrating biofertilizer with organic amendments can sustainably enhance soil fertility and support intensive cultivation in fallow or organically managed land. Practically, this approach provides a cost-effective strategy for improving soil quality and crop productivity, contributing to sustainable agricultural management.

Acknowledgments
Gratitude is extended to the Ministry of Education, Culture, Research, and Technology for funding this research and community service program under the 2024 fiscal year, within the main research scope in the food sector (Grant Number 0459/E5/PG.02.00/2024) and Agreement/Contract Numbers 105/E5/PG.02.00.PL/2024 (dated June 11, 2024), 795/LL3/AL.04/2024 (dated June 26, 2024), and 22.1/LP/UG/VI/2024. Special thanks are also given to Gunadarma Technopark University for providing the research site.

Author Contributions
Conceptualization, AIS; methodology, AIS; software, PAS; validation, AIS and PAS; formal analysis, AIS; investigation, PAS; resources, FIT; data curation, AIS; writing—original draft preparation, PAS; writing—review and editing, PAS; visualization, PAS; supervision, FIT; project administration, FIT; funding acquisition, FIT; pest management, RIS. All authors have read and agreed to the published version of the manuscript.

Funding
This research was made possible through the generous funding support of the Directorate of Research and Community Service, Indonesian Ministry of Education, Culture, Research, and Technology, under the Regular Fundamental Research scheme (Master Contract: 104/C3/DT.05.00/PL/2025; Subcontract: 541/UN54.6/PT.01.03/2025). The author sincerely appreciates this contribution to the advancement of educational research.

Conflicts of Interest
The authors declare no conflict of interest.

References

Aisyah, K., R., & Sari, E. R. (2018). Lama Inkubasi Pupuk Kandang Kambing Pada Tanah Tercemar Logam Berat'. *Jurnal Pertanian Presisi (Journal of Precision Agriculture)*, *2*(1), 21–34. https://doi.org/10.35760/jpp.2018.v2i1.2004

Arfarita, N., Lestari, M. W., & Prayogo, C. (2020). Utilization of vermiwash for the production of liquid biofertilizers and its effect on viability of inoculant bacteria and green bean germination'. *Agrivita*, *42*(1), 120–130. https://doi.org/10.17503/agrivita.v42i1.2263

Chen, M., Zhang, S., Liu, L., Liu, J., & Ding, X. (2022). Organic fertilization increased soil organic carbon stability and sequestration by improving aggregate stability and iron oxide transformation in saline-alkaline soil'. *Plant and Soil*, *474*(1), 233–249. https://doi.org/10.1007/s11104-022-05326-3

Corbett, D. (2022). The influence of phosphorus application and varying soil pH on soil and herbage properties across a range of grassland soils with impeded drainage'. *Journal of Agricultural Science*, *160*(6), 516–527. https://doi.org/10.1017/S0021859622000363

Cui, X., Zhang, Y., Gao, J., Peng, F., & Gao, P. (2018). Long-term combined application of manure and chemical fertilizer sustained higher nutrient status and rhizospheric bacterial diversity in reddish paddy soil of Central South China'. *Scientific Reports*, *8*(1), 16554. https://doi.org/10.1038/s41598-018-34685-0

Da Cunha Leme Filho, J. F., Chim, B. K., Bermand, C., Diatta, A. A., & Thomason, W. E. (2024). Effect of organic biostimulants on cannabis productivity and soil microbial activity under outdoor conditions'. *Journal of Cannabis Research*, *6*(1), 16. https://doi.org/10.1186/s42238-024-00214-2

Daniel, A. I. (2022). Biofertilizer: The Future of Food Security and Food Safety'. *Microorganisms*. https://doi.org/10.3390/microorganisms10061220

Debska, B. (2016). The impact of a bio-fertilizer on the soil organic matter status and carbon sequestration—results from a field-scale study'. *Journal of Soils and Sediments*, *16*. https://doi.org/10.1007/s11368-016-1430-5

Dikinya, O., & Mufwanzala, N. (2010). Chicken manure-enhanced soil fertility and productivity: Effects of application rates'. *Journal of Soil Science and Environmental Management*, *1*(3), 46–54. Retrieved from https://academicjournals.org/journal/JSSEM/article-full-text-pdf/F47E1839575.pdf

Fitriatin, B. N., Dewi, V. F., & Yuniarti, A. (2021). The Impact of Biofertilizers and NPK Fertilizers Application on Soil Phosphorus Availability and Yield of Upland Rice in Tropic Dry Land'. *E3S Web of Conferences*, 232. https://doi.org/10.1051/e3sconf/202123203012

Guan, X. (2023). Mixed organic and inorganic amendments enhance soil microbial interactions and environmental stress resistance of Tibetan barley on plateau farmland'. *Journal of Environmental Management*, *330*, 117137. https://doi.org/10.1016/j.jenvman.2022.117137

Guo, Q., Fang, X., Wang, L., Zhang, E., & Liu, Z. (2023). Robust fusion for skin lesion segmentation of dermoscopic images'. *Frontiers in Bioengineering and Biotechnology*, *11*, 1–14. https://doi.org/10.3389/fbioe.2023.1057866

Haibin, W., Zhengtang, G., & Changhui, P. (2001). Changes in Terrestrial Carbon Storage With Global Climate Changes Since The Last Interglacial'. *Quaternary Sciences*, *21*(4), 366–376. Retrieved from http://www.dsjyj.com.cn//article/id/dsjyj_9432

Hamed, M. H., Desoky, M. A., Ghallab, A. M., & Faragallah, M. A. (2014). Effect of Incubation Periods and Some Organic Materials on Phosphorus Forms in Calcareous Soils'. *International Journal of Technology Enhancements and Emerging Engineering Research*, *2*(6), 108. Retrieved from https://www.researchgate.net/publication/322307955

Harsani, H., Zulkifli, Z., & Putera, M. I. (2023). Dinamika Status Hara Lahan Kering Menggunakan Tabung Hara Biochar Bermikoriza', Agroplantae: Jurnal Ilmiah Terapan Budidaya dan Pengelolaan Tanaman Pertanian dan. *Perkebunan*, *12*(2), 171–180. https://doi.org/10.51978/agro.v12i2.691

He, H., Peng, M., Hou, Z., & Li, J. (2024). Unlike chemical fertilizer reduction, organic fertilizer substitution increases soil organic carbon stock and soil fertility in wheat fields'. *Journal of the Science of Food and Agriculture*, *104*(5), 2798–2808. https://doi.org/10.1002/jsfa.13167

Hossain, M. E. (2021). Substitution of Chemical Fertilizer with Organic Fertilizer Affects Soil Total Nitrogen and Its Fractions in Northern China'. *International Journal of Environmental Research and Public Health*. https://doi.org/10.3390/ijerph182312848

Husni, H., Septiani, W., & Tamzi, F. (2022). Dinamika Simpanan Karbon dan Kepadatan Tanah Setelah Pengolahan Tanah'. *Jurnal Agroecotania : Publikasi Nasional Ilmu Budidaya Pertanian*, *4*(1), 38–48. https://doi.org/10.22437/agroecotania.v4i1.20434

Indriana, K. R., Dirmawan, R. H., & Komariah, A. (2021). Pengaruh Konsentrasi Pupuk Hayati Bioboost dan Air Kelapa Terhadap Pertumbuhan dan Hasil Tanaman Selada (Lactuca sativa L.) Varietas Grand Rapids. *Jurnal Agroscience*, *11*(1), 1–13. Retrieved from https://pdfs.semanticscholar.org/3bdc/a134806d1c1b57260432c3801c3785d98ee6.pdf

Jones, D. L., & Oburger, E. (2010). Solubilization of phosphorus by soil microorganisms. In *Phosphorus in action: biological processes in soil phosphorus cycling* (pp. 169–198). Springer. https://doi.org/10.1007/978-3-642-15271-9_7

Kaur, A. (2024). Developing a Hybrid Irrigation System for Smart Agriculture Using IoT Sensors and Machine Learning in Sri Ganganagar, Rajasthan'. *Journal of Sensors*. https://doi.org/10.1155/2024/6676907

Kuziemska, B., Wysokiński, A., & Trębicka, J. (2020). The effect of different copper doses and organic fertilisation on soil's enzymatic activity. *Plant, Soil and Environment*, *66*(2), 93–98. https://doi.org/10.17221/671/2019-PSE

Li, J., Cooper, J. M., Lin, Z. A., Li, Y., Yang, X., & Zhao, B. (2015). Soil microbial community structure and function are significantly affected by long-term organic and mineral fertilization regimes in the North China Plain'. *Applied Soil Ecology*, *96*, 75–87. https://doi.org/10.1016/j.apsoil.2015.07.001

Li, X., Fang, J., Shagahaleh, H., Wang, J., Hamad, A. A. A., & Alhaj Hamoud, Y. (2023). Impacts of Partial Substitution of Chemical Fertilizer with Organic Fertilizer on Soil Organic Carbon Composition, Enzyme Activity, and Grain Yield in Wheat–Maize Rotation'. *Life*, *13*(9), 1929. https://doi.org/10.3390/life13091929

Ma, G., Cheng, S., He, W., Dong, Y., Qi, S., Tu, N., & Tao, W. (2023). Effects of Organic and Inorganic Fertilizers on Soil Nutrient Conditions in Rice Fields with Varying Soil Fertility'. *Land*, *12*(5). https://doi.org/10.3390/land12051026

Manoj, S., Thirumurugan, M., & Elango, L. (2020).

Determination of distribution coefficient of uranium from physical and chemical properties of soil. *Chemosphere*, *244*, 125411. https://doi.org/10.1016/j.chemosphere.2019.125411

Muktamar, Z., & Lifia, T. A. (2020). Phosphorus availability as affected by the application of organic amendments in Ultisols'. *Sains Tanah*, *17*(1), 16–22. https://doi.org/10.20961/stjssa.v17i1.41284.

Opala, P. A., Okalebo, J. R., & Othieno, C. O. (2012). Effects of Organic and Inorganic Materials on Soil Acidity and Phosphorus Availability in a Soil Incubation Study'. *ISRN Agronomy*, 1–10. https://doi.org/10.5402/2012/597216

Patriani, P., Hasanah, U., & Wahyuni, T. H. (2022). Bokashi Application for Organic Farming in Manuk Mulia Village, Karo District'. *Journal of Saintech Transfer*, *5*(1), 40–48. https://doi.org/10.32734/jst.v5i1.8851

Qaswar, M., Jing, H., Ahmed, W., Dongchu, L., Shujun, L., Lu, Z., & Huimin, Z. (2020). Yield sustainability, soil organic carbon sequestration and nutrients balance under long-term combined application of manure and inorganic fertilizers in acidic paddy soil'. *Soil and Tillage Research*, *198*, 104569. https://doi.org/10.1016/j.still.2019.104569

Salma, D., Venkaiah, K., Naidu, M., & Ramu, Y. (2018). Soil Physical Properties and Groundnut (Arachis hypogae L.) Yield under Long- Term Application of Manure and Fertilizers under Rainfed Condition'. *International Journal of Plant & Soil Science*, *22*(5), 1–8. https://doi.org/10.9734/ijpss/2018/40859

Sanchez, P. A. (2019). *Properties and Management of Soils in the Tropics'*. Cambridge University Press.

Saputri, K. E., Idiawati, N. S., & Juane Sofiana, M. S. (2021). Isolasi dan Karakterisasi Bakteri Penambat Nitrogen dari Rizosfer Mangrove di Kuala Singkawang'. *Jurnal Laut Khatulistiwa*, *4*(2), 80. https://doi.org/10.26418/lkuntan.v4i2.45316

Shi, Y., Niu, X., Chen, B., Pu, S., Ma, H., Li, P., & Ma, X. (2023). Chemical fertilizer reduction combined with organic fertilizer affects the soil microbial community and diversity and yield of cotton.'. *Frontiers in Microbiology*, *14*, 1295722. https://doi.org/10.3389/fmicb.2023.1295722

Siregar, P., Fauzi, & Suproadi. (2017). Pengaruh Pemberian Beberapa Sumber Bahan Organik Dan Masa Inkubasi Terhadap Beberapa Aspek Kimia Kesuburan Tanah Ultisol (The Effect of Giving Several Sources of Organic Material and Incubation Period on Some Chemical Aspects of Ultisol Soil Fertility)'. *Jurnal Agroekoteknologi Universitas Sumatera Utara*, *5*(2), 256–264. Retrieved from https://talenta.usu.ac.id/joa/article/view/2541

Tan, K. H. (2010). *Principles of Soil Chemistry* (4th Editio). Taylor & Francis. https://doi.org/10.1201/9781439894606

Thomas, G. W., & Hipp, B. W. (1968). Soil factors affecting potassium availability. *The Role of Potassium in Agriculture*, 269–291. https://doi.org/10.2134/1968.roleofpotassium.c13

Tong, Y. (2024). Enhancing Soil Fertility and Elevating Pecan Fruit Quality through Combined Chemical and Organic Fertilization Practices'. *Horticulturae*. https://doi.org/10.3390/horticulturae10010025

Wan, L. J., Tian, Y., He, M., Zheng, Y. Q., Lyu, Q., Xie, R. J., & Yi, S. L. (2021). Effects of Chemical Fertilizer Combined with Organic Fertilizer Application on Soil Properties, Citrus Growth Physiology, and Yield'. *Agriculture*, *11*(12), 1207. https://doi.org/10.3390/agriculture11121207

Wang, B., Gao, Y., Yuan, X., Xiong, S., & Feng, X. (2020). From species to cultivar: Soybean cultivar recognition using joint leaf image patterns by multiscale sliding chord matching'. *Biosystems Engineering*, *194*, 99–111. https://doi.org/10.1016/j.biosystemseng.2020.03.019

Wang, R., Hou, T., Sun, Q., Ji, L., Lei, J., & Zhang, J. (2021). Organic Fertilizers and Soil Conditioner Recover Chemical Fertilizer-Induced Changes in Soil Bacterial Community Diversity in Wine Grape Rhizosphere Soil'. *Polish Journal of Environmental Studies*, *30*(2), 1853–1863. https://doi.org/10.15244/pjoes/126236

Wen, Y. C., Li, H. Y., Lin, Z. A., Zhao, B. Q., Sun, Z. B., Yuan, L., & Li, Y. Q. (2020). Long-term fertilization alters soil properties and fungal community composition in fluvo-aquic soil of the North China Plain'. *Scientific Reports*, *10*(1), 7198. https://doi.org/10.1038/s41598-020-64227-6

Wu, L., Jiang, Y., Zhao, F., He, X., Liu, H., & Yu, K. (2020). Increased organic fertilizer application and reduced chemical fertilizer application affect the soil properties and bacterial communities of grape rhizosphere soil'. *Scientific Reports*, *10*(1), 9568. https://doi.org/10.1038/s41598-020-66648-9

Xu, Y., Sun, L., Gao, X., & Wang, J. (2022). Contrasting response of fungal versus bacterial residue accumulation within soil aggregates to long-term fertilization'. *Scientific Reports*, *12*(1), 17834. https://doi.org/10.1038/s41598-022-22064-9

Ye, L., Zhao, X., Bao, E., Li, J., Zou, Z., & Cao, K. (2020). Bio-organic fertilizer with reduced rates of chemical fertilization improves soil fertility and enhances tomato yield and quality'. *Scientific Reports*, *10*(1), 177. https://doi.org/10.1038/s41598-019-56954-2