

Experiment on the Effect of Pineapple Ecoenzyme on the Morphological Growth of Green Beans (*Vigna radiata* L.) as an Effort to Promote Environmentally Friendly Fertilization

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Abstract: This study aims to analyze the effectiveness of pineapple peel waste-based ecoenzymes as liquid organic fertilizer on the height growth of mung beans (*Vigna radiata* L.). Ecoenzymes are the result of organic waste fermentation with carbon sources from sugar and water, produced through the activity of decomposing microbes. The compounds contained therein, such as enzymes, organic acids, and beneficial microorganisms, play an important role in increasing soil biological activity, improving soil structure, and accelerating the absorption of nutrients by plant roots. The research was conducted in a laboratory experiment using a three-main-treatment design, namely: control without fertilizer, application of pineapple ecoenzyme liquid organic fertilizer, and application of EM4 liquid organic fertilizer as a commercial comparison. Observations were made every two days during a 14-day period, focusing on the variable of plant height increase. The results showed that the pineapple ecoenzyme treatment significantly increased vegetative plant growth, with an average growth of 10.40 cm, higher than the control (6.20 cm) and close to the EM4 results (11.10 cm). These findings confirm that pineapple ecoenzyme has the potential to be an environmentally friendly liquid organic fertilizer alternative, which not only supports plant growth but also contributes to sustainable household organic waste management.

Keywords: Ecoenzyme; Green beans; Liquid organic fertilizer; Pineapple peel waste; Vegetative growth

Introduction

The presence of waste is one of the main problems faced by modern society, especially in urban areas with high consumption levels. In the context of sustainability and environmental protection, the issue of waste management is crucial. Waste that is not managed properly can have various negative impacts on cleanliness, health, comfort, and the aesthetics of the environment (Muqsit et al., 2024; Kitole et al., 2024). Piles of waste in public spaces such as roads, parks, and waterways not only create a dirty impression but also have the potential to become a source of disease due to the growth of pathogenic microorganisms and vectors (Paz, 2024; Yan et al., 2024). One type of household waste that dominates solid waste accumulation is organic

waste, which includes food scraps, vegetables, dry leaves, and fruit peels. If not properly processed, organic waste can undergo anaerobic decomposition, producing methane (CH₄) gas—a greenhouse gas with a global warming potential 25 times greater than carbon dioxide (Erika Erika & Eva Gusmira, 2024; Waheed et al., 2023). The open burning of organic waste, which is often carried out by the community, also worsens atmospheric conditions by increasing levels of carbon monoxide and fine particulate matter (PM_{2.5}), which are harmful to respiratory health.

One innovation that has emerged as an environmentally friendly solution for organic waste management is ecoenzymes. Ecoenzymes are liquids produced by fermenting organic materials such as vegetables or fruits with the addition of carbon sources such as brown sugar, molasses, or granulated sugar in

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certain proportions (Mgeni et al., 2024; Esercizio et al., 2021). This fermentation process produces enzymes and organic acids that are useful in accelerating the decomposition of organic materials, suppressing the growth of pathogenic microbes, and increasing the availability of nutrients for plants (Marzouk et al., 2025; Chen et al., 2024). The method of processing organic waste into ecoenzymes was first developed by Dr. Rosukon Poompanvong from Thailand in 2003 and was recognized by the Food and Agriculture Organization (FAO) for its contribution to sustainable agriculture (Hiywotu, 2025; Guggisberg, 2022).

In the context of sustainable agriculture, ecoenzymes not only function as waste decomposing agents but can also be utilized as liquid organic fertilizers (LOF). Liquid organic fertilizer has a number of advantages over solid organic fertilizer, including: nutrient content that is more easily absorbed by plants, more practical application, and relatively short fermentation time (Maintang et al., 2021; Syllistiana, 2025). The active microorganisms in liquid organic fertilizer also play an important role in improving soil structure and increasing biological activity in the rhizosphere (Guo et al., 2025; Sun et al., 2024). Pineapple peel is one of the abundant agricultural and household wastes that is often discarded. In fact, pineapple peel contains bromelain enzymes, vitamin C, amino acids, and minerals that can be used as the main ingredients for making ecoenzymes (Gharge et al., 2024). Bromelain enzymes are known to accelerate the decomposition of organic matter and aid in the absorption of nitrogen and phosphorus by plants (Zhou et al., 2022). Thus, the production of pineapple peel-based ecoenzymes can be an innovative approach to utilizing fruit waste while providing an effective source of liquid organic fertilizer for plants.

One of the indicator plants often used in organic fertilization research is mung beans (*Vigna radiata* L.), due to their short life cycle, responsiveness to environmental changes, and ease of observation during the vegetative growth phase (Islam et al., 2021). Therefore, this study was conducted to analyze the effectiveness of ecoenzymes made from pineapple peel waste as liquid organic fertilizer on the height increase of mung bean plants. The results of this study are expected to provide a real contribution to community-based organic waste management efforts and support the implementation of environmentally friendly agriculture towards sustainable development.

Method

Type and Method of Research

Type of Research

This study belongs to the qualitative descriptive research design, which aims to portray phenomena

comprehensively and deeply under natural conditions without complex manipulation of variables. According to Bogdan and Taylor (as cited in (Aguinis & Solarino, 2019)), the qualitative approach emphasizes data collection in the form of written or spoken words, as well as direct observation of behavior and environmental context. Furthermore, Descriptive qualitative research is grounded in the post-positivist paradigm and is carried out within a natural setting where the researcher acts as the main instrument. This research design allows a detailed exploration of how eco-enzyme made from pineapple peel waste functions as a liquid organic fertilizer and how its application influences the growth performance of green bean (*Vigna radiata* L.) plants. The descriptive qualitative approach was chosen to enable a comprehensive understanding of plant responses and environmental interactions that occur during the experimental period.

Research Method

The research applied a simple experimental method supported by a qualitative descriptive analysis. The experimental procedure was designed to observe and compare the growth of plants treated with eco-enzyme-based liquid organic fertilizer and a commercial bio-activator (EM4), along with a control group that received no fertilizer treatment. This methodological choice provides a direct means to evaluate the effectiveness of the eco-enzyme formulation derived from pineapple peel waste and to assess its potential role as an environmentally friendly organic fertilizer. The experimental design enables a focused observation of growth indicators such as plant height, number of leaves, leaf coloration, and overall plant condition throughout the research period. The use of a simple experimental setup facilitates the identification of observable trends without requiring a large-scale factorial design. By emphasizing qualitative observation, this study bridges the gap between empirical laboratory research and real-world ecological application, aligning with recent literature on sustainable bio-fertilizer production.

Time and Location of Research

The research was conducted on Monday, May 19, 2025, at the Science Laboratory of Pondok Pesantren Raudlatul Musthofa, Tulungagung, Indonesia. The laboratory setting was selected to maintain a controlled and uniform environmental condition during the experimental process, minimizing the influence of external factors such as light, humidity, and soil variation. Conducting the experiment in a semi-controlled laboratory environment ensured consistent monitoring of plant growth and the reliability of observed differences among treatment groups.

Tools and Materials

Tools

The experimental tools consisted of two spray bottles (500–1000 ml capacity) for applying the liquid fertilizer, one measuring instrument such as a graduated cylinder or volumetric pipette for dosage accuracy, and several recycled plastic bottles (e.g., Aqua bottles) as storage containers for the fertilizer solution. Each tool was properly cleaned and sterilized before use to prevent contamination during the experiment.

Materials

Materials used included 500 ml of ready-to-use pineapple peel eco-enzyme, 10 ml of commercial EM4 liquid bio-activator, and 500 ml of clean water for dilution, depending on concentration requirements. The biological samples consisted of three green bean plants (*Vigna radiata L.*) of similar age and morphological characteristics to ensure comparability between treatments. These materials were selected for their availability, eco-friendliness, and proven relevance to previous studies on organic fertilizer development.

Experimental Procedures

Preparation of Eco-Enzyme and EM4 Mixture

The fertilizer treatment solution was prepared by mixing 500 ml of eco-enzyme with 10 ml of EM4. The mixture was stirred thoroughly until homogeneous and then sealed for 24 hours to allow further fermentation. The solution was divided into two labeled containers: Bottle A: Eco-enzyme + EM4 mixture; Bottle B: Pure eco-enzyme (without EM4, serving as partial control). This process followed the basic fermentation principles ensuring microbial activation prior to plant application.

Fertilization and Observation Procedures

Three green bean plants with uniform age and size were assigned to different treatment groups as follows: Plant A: Treated with Eco-enzyme + EM4 mixture; Plant B: Treated with Eco-enzyme only; Plant C: Control (no fertilizer application). Fertilization was performed twice a week for one month, using the same concentration for both treatment groups. Observations were conducted daily during the first week and every two days thereafter for the next three weeks. Parameters observed included plant height, number of leaves, leaf color, and general plant conditions (stem and root health). The data collected were then organized into observational tables and qualitative growth summaries.

Data Analysis

The data obtained were analyzed using qualitative descriptive techniques, emphasizing comparative interpretation between treatments. The analysis involved identifying growth differences among plants, describing observable patterns, and correlating them

with potential nutrient availability provided by the eco-enzyme. The qualitative approach allowed in-depth discussion of ecological and physiological implications supported by previous studies. The interpretation was contextualized with findings from similar research to ensure theoretical and empirical consistency. The overall workflow of this study is illustrated in Figure 1, which presents the sequence of activities conducted during the research process. The diagram visually demonstrates how each stage is interconnected starting from the preparation phase, experimental setup, data observation, and qualitative analysis, leading to the final interpretation of results.

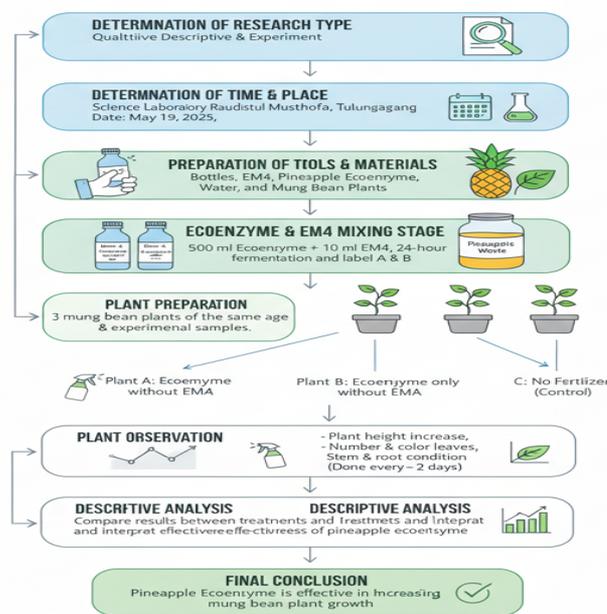


Figure 1. Research Procedure Flowchart

This figure shows the experimental steps of the study on the effectiveness of pineapple-based eco-enzyme as a liquid organic fertilizer on mung bean (*Vigna radiata L.*) growth, from preparation, treatment, observation, to data analysis.

Result and Discussion

Research Results

This study began on May 19, 2025, with the initial stage of green bean (*Vigna radiata L.*) seed germination using wet cotton as the medium. Cotton was chosen as the initial medium for a reason; it has high water absorption and is able to maintain a stable level of humidity, which is very important in the physiological process of seeds during imbibition and germination (Pompelli et al., 2023). Moist media conditions with good aeration allow for optimal biochemical activities such as enzyme hydration, cell division, and elongation of the hypocotyl and radicle tissues (Mildaziene et al., 2022).

After an incubation period of seven days, on May 26, 2025, the mung bean seeds showed sprout growth with an average length of about 7 cm. This indicates that the germination process was effective and marks the success of the initial physiological stage of the plant. According to research by (Wawrzyniak et al., 2020) sprout growth in the 6–8 cm length range indicates high seed viability and a positive response to supportive media conditions. The next stage involved transferring the sprouts to soil media in polybags to facilitate further growth in an environment more similar to natural conditions.

The growing medium used was a mixture of loose soil and compost with a ratio of 2:1, aiming to improve soil aeration while enriching macro nutrients such as nitrogen (N), phosphorus (P), and potassium (K), which are essential for vegetative plant growth (Kumar et al., 2021). During the treatment phase, the plants were divided into three different groups, namely: Control group, without additional fertilizer; Group with ecoenzyme liquid organic fertilizer (POC) made from pineapple peel waste; Group with a mixture of

ecoenzyme and EM4 (Effective Microorganisms 4). The purpose of this treatment was to evaluate the effect of organic nutrients on plant morphological growth parameters, including stem height, number of leaves, leaf color, and stem condition. Observations were conducted daily during the first week (May 26–June 1, 2025), then every two days during the second week (June 2–8, 2025).

This repeated observation design allows for the analysis of plant growth dynamics over time and distinguishes the effects of each treatment quantitatively and qualitatively (Wei et al., 2024). The use of ecoenzymes and EM4 is expected to increase soil microorganism activity and accelerate the decomposition of organic matter, making nutrients more easily absorbed by plant roots (Lange et al., 2015). Thus, this study not only assesses mung bean growth as a biological indicator but also confirms the potential use of fermented organic waste as an environmentally friendly fertilizer to support agriculture.

Table 1. Growth of Mung Bean Plants During the First Week (May 26 – June 1, 2025)

Day	Date	Plant 1 (Control)	Plant 2 (Ecoenzyme)	Plant 3 (Ecoenzyme + EM4)
1	May 26, 2025	Height 7 cm, 4 leaves, light green color	Height 7 cm, 4 leaves, fresh green color	Height 7 cm, 4 leaves, fresh green color
2	May 27, 2025	Height 7.20 cm, 4 leaves	Height 7.50 cm, 5 leaves, stem becoming sturdy	Height 7.80 cm, 5 leaves, shiny leaves
3	May 28, 2025	Height 7.50 cm, 4 leaves, slightly pale	Height 8 cm, 5 leaves, stable growth	Height 8.50 cm, 6 leaves, upright stem
4	May 29, 2025	Height 7.80 cm, 5 leaves	Height 9 cm, 6 leaves, bright green color	Height 9.50 cm, 6 leaves, brighter color
5	May 30, 2025	Height 8 cm, 5 leaves, thin stem	Height 10 cm, 7 leaves, fresh green color	Height 10.50 cm, 8 leaves, broad leaves
6	May 31, 2025	Height 8.20 cm, 6 leaves, pale color	Height 11 cm, 7 leaves, thicker stem	Height 12 cm, 8 leaves, rapid growth
7	June 1, 2025	Height 8.50 cm, 6 leaves, slightly wilted	Height 12 cm, 8 leaves, dark green color	Height 13 cm, 9 leaves, fresh and glossy appearance

Table 1 presents the growth performance of mung bean plants (*Vigna radiata L.*) during the first week of observation (26 May – 1 June 2025) under three different treatments: control, ecoenzyme, and ecoenzyme combined with EM4. The data indicate a clear variation in growth patterns among treatments, both in terms of height and leaf development. The control plants exhibited the slowest rate of growth, with an average height increase of only 1.50 cm throughout the first week. Their leaves appear pale green and slightly wilted, suggesting nutrient deficiency and limited photosynthetic activity. Such symptoms commonly occur when the soil lacks essential macronutrients such as nitrogen and phosphorus, which are required for vegetative development (Bhat et al., 2024; De Bang et al., 2021). The weak stem structure and yellowish leaf color also indicate suboptimal physiological function in the

absence of fertilizer supplementation. In contrast, plants treated with the ecoenzyme solution showed a more stable growth pattern, increasing in height from 7 cm to 12 cm by the end of the first week. The leaves were greener and fresher, and the stems appeared thicker and more upright. This improvement reflects the role of the enzymatic components in ecoenzyme—such as amylase, protease, and lipase—in enhancing soil fertility and promoting nutrient availability (Rachman et al., 2025). The organic acids and natural hormones present in ecoenzymes, including auxins and cytokinins, are also known to stimulate cell elongation and chlorophyll formation, which may explain the healthier leaf coloration (Li et al., 2021).

The plants treated with a combination of ecoenzyme and EM4 demonstrated the highest growth performance among all treatments. By the seventh day,

these plants reached an average height of 13 cm, with nine dark-green, glossy leaves and sturdy stems. The improved vigor can be attributed to the synergistic interaction between the enzymatic compounds in the ecoenzyme and the beneficial microorganisms present in EM4, such as *Lactobacillus sp.*, *Saccharomyces sp.*, and *Rhodopseudomonas sp.*, which contributes to nutrient cycling and soil microbial balance (Suman et al., 2022). Overall, the analysis of Table 1 shows that the combination of ecoenzyme and EM4 provides the most

effective enhancement of early vegetative growth in mung bean plants. These findings align with (Nanda et al., 2025), who emphasized that organic enzyme-based bioactivators can improve soil structure, increase nutrient absorption efficiency, and promote more sustainable plant development. The results also confirm that ecoenzyme, when fortified with EM4, acts as a natural growth stimulant capable of accelerating germination and early.

Table 2. Growth of Mung Bean Plants During the Second Week (2–8 June 2025)

Day	Date	Plant 1 (Control)	Plant 2 (Ecoenzyme)	Plant 3 (Ecoenzyme + EM4)
9	2 June 2025	Height 9 cm, 6 leaves, pale	Height 13 cm, 9 leaves, fresh	Height 14.50 cm, 10 leaves, broad and sturdy
11	4 June 2025	Height 9.20 cm, 7 leaves, yellowing	Height 14 cm, 10 leaves, stable	Height 16 cm, 11 leaves, upright and healthy
13	6 June 2025	Height 9.50 cm, 7 leaves, growth slowed	Height 15 cm, 10 leaves, broad	Height 17.50 cm, 12 leaves, dense and bright
15	8 June 2025	Height 9.70 cm, 7 leaves, pale	Height 15.50 cm, 10 leaves, elongated	Height 18.50 cm, 13 leaves, lush and healthy

Table 2 illustrates the second phase of observation (2–8 June 2025), showing more pronounced differences in plant performance across treatments compared with the first week. The data clearly shows that ecoenzyme-based treatments continued to enhance vegetative growth, while the control plants remained stagnant. The control plants exhibited minimal growth, with total height increasing only 0.70 cm (from 9.00 to 9.70 cm) and no visible improvement in leaf number or color. The persistent pale and yellowing leaves indicate chlorosis and nutrient depletion, likely caused by the lack of nitrogen supply for chlorophyll synthesis (Yoneyama, 2021). This stagnation suggests that soil nutrient reserves were insufficient to sustain photosynthetic activity after the first week of growth. The ecoenzyme-treated plants displayed moderate but consistent progress, reaching 15.50 cm in height and maintaining ten healthy leaves by the end of the second week.

The green coloration and elongated leaves reflect improved chlorophyll production and enhanced water uptake, supported by the enzymatic compounds derived from fermented pineapple peel. These enzymes promote the decomposition of organic matter into simpler forms of nutrients that are readily absorbed by plant (Das et al., 2025). Meanwhile, the ecoenzyme + EM4 plants achieved the most vigorous development, growing from 14.50 cm to 18.50 cm and producing up to 13 dense, glossy leaves. Their stems were thicker and sturdier, indicating strengthened structural tissues. This outcome can be attributed to the synergistic effect between the enzymes in ecoenzyme and the beneficial microbes in EM4 (*Lactobacillus sp.*, *Rhodopseudomonas sp.*, *Saccharomyces sp.*), which enhances nutrient

mineralization and nitrogen fixation in the rhizosphere. The significant improvement observed in the ecoenzyme + EM4 treatment supports the hypothesis that combining enzyme and microbial bioactivators creates an optimal environment for nutrient cycling and plant growth.

The increased leaf density and vivid green coloration are strong indicators of elevated photosynthetic efficiency and better physiological adaptation. These findings reinforce previous studies by (Li et al., 2021) who reported that organic enzymes can improve soil structure, increase microbial diversity, and accelerate nutrient absorption. In this study, the combination of ecoenzyme and EM4 not only promoted faster vertical growth but also enhanced the overall vigor and resilience of mung bean plants under controlled conditions. Thus, the use of ecoenzyme-based organic liquid fertilizer—especially when enriched with EM4—can be considered as a sustainable and eco-friendly innovation to optimize early vegetative development.

Discussion

The overall findings of this study reveal that the application of liquid organic fertilizer derived from pineapple peel eco-enzyme has a remarkable positive influence on the early vegetative growth of mung bean (*Vigna radiata*) plants, especially when it is combined with EM4 (Effective Microorganisms 4). The treatment combining eco-enzyme and EM4 consistently produced taller plants, more leaves, and stronger stems compared to both the eco-enzyme-only and control treatments. This improvement can be attributed to the unique

biochemical composition of eco-enzyme, which contains various organic acids, proteolytic enzymes, amino acids, antioxidants, and naturally occurring plant growth regulators such as auxins, cytokinins, and gibberellins. These compounds collectively stimulate cell elongation, promote meristematic activity, enhance root branching, and accelerate tissue differentiation (Jia et al., 2022). Through these physiological mechanisms, eco-enzyme serves as both a nutrient source and a biostimulant that optimizes plant growth conditions.

Furthermore, the inclusion of EM4 intensifies the beneficial effects of eco-enzyme due to the presence of active microbial consortia such as *Lactobacillus sp.*, *Saccharomyces sp.*, and *Rhodopseudomonas sp.* These microorganisms play a crucial role in decomposing organic matter, producing bioactive metabolites, and converting complex nutrients into simpler forms that are easily absorbed by plant roots (Martínez-Chávez et al., 2024). EM4 also enhances the microbial diversity of the rhizosphere, leading to improved soil aggregation, aeration, and nutrient retention. The combined application of eco-enzyme and EM4 thus forms a symbiotic system where chemical, biological, and physical soil properties interact harmoniously to support sustainable plant growth. This synergy is evident in the second-week observations, where the eco-enzyme + EM4 group demonstrated the highest increase in plant height and leaf number, along with visibly healthier and more vibrant leaf color.

The dark green leaves and sturdy stems observed in the treated plants are indicators of elevated chlorophyll synthesis and enhanced photosynthetic capacity. As stated by (Desmanto et al., 2024), the chlorophyll content of a plant is directly related to its ability to assimilate carbon dioxide and produce biomass through photosynthesis. The eco-enzyme likely supplied additional micronutrients such as iron, manganese, and zinc—essential cofactors in chlorophyll biosynthesis—thereby contributing to this improvement. Additionally, organic acids present in the eco-enzyme, including citric and lactic acids, may have increased the solubility and mobility of nutrients like nitrogen and phosphorus in the soil solution, facilitating better uptake and utilization by the roots. In contrast, the control group, which did not receive any eco-enzyme or EM4 treatment, exhibited the slowest growth, paler leaves, and reduced vigor. This condition suggests nutrient deficiency and low microbial activity in the soil, leading to limited nutrient absorption and suboptimal metabolic processes. (Sherzad et al., 2025) emphasizes that such limitations result in the inhibition of chlorophyll formation, enzyme synthesis, and cell proliferation, which collectively suppress vegetative development. Therefore, the differences between treatments underline the critical role of organic

biofertilizers in restoring soil vitality and promoting healthy plant physiology.

From an environmental and sustainability perspective, the use of eco-enzyme derived from pineapple peel waste aligns perfectly with the principles of circular economy and eco-friendly agriculture. Pineapple peel, often discarded as a by-product of household and industrial processing, can be transformed through fermentation into a valuable biofertilizer. This approach not only provides an economical alternative to chemical fertilizers but also reduces the volume of organic waste, mitigates landfill emissions, and prevents the contamination of surrounding ecosystems (Aljarrah et al., 2024). Moreover, the fermentation process itself produces minimal waste and contributes to microbial enrichment, creating a closed-loop system that supports long-term agricultural sustainability. The implications of this research are in line with the findings of (Amrullah et al., 2021), who reported that organic fertilizers obtained from natural fermentation can significantly enhance soil fertility, increase microbial populations, and improve the physiological performance of crops.

Similar studies have also demonstrated that eco-enzymes derived from fruit waste can enhance enzymatic activity in soil, improve root nodulation in legumes, and increase nitrogen fixation efficiency. These cumulative effects ultimately lead to higher yields, better crop quality, and more resilient plants under varying environmental conditions. Therefore, based on the experimental results and supporting literature, it can be concluded that the combination of eco-enzyme and EM4 acts as an effective bioactivator for mung bean cultivation. This combination not only accelerates vegetative growth but also enhances the biochemical and microbiological properties of the soil. In the long term, continuous application of eco-enzyme + EM4 could reduce dependency on synthetic fertilizers, preserve soil biodiversity, and maintain ecological balance in agricultural systems. Thus, this innovation represents a promising step toward sustainable, low-cost, and environmentally responsible farming practices that support both productivity and ecological health.

Conclusion

The combined application of liquid organic fertilizer eco-enzyme pineapple peel and Effective Microorganisms 4 (EM4) is a highly effective and superior bioactivator to encourage the early vegetative growth of mung bean plants (*Vigna radiata* L) in a sustainable manner. The combination of eco-enzyme and EM4 creates a symbiotic system that improves the chemical, biological, and physical properties of the soil, resulting in optimal plant physiological performance and is a promising innovation towards sustainable, low-

cost, and environmentally responsible agricultural practices.

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Author Contributions

Conceptualization, methodology,; formal analysis,; investigation, resources,; writing—preparation of original draft; writing—reviewing and editing,; visualization, supervision,; project administration, obtaining funding F. P. All authors have read and approved the published version of the manuscript.

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Conflict of Interest

The author declares that there is no conflict of interest in publishing this scientific article.

References

- Aguinis, H., & Solarino, A. M. (2019). Transparency and replicability in qualitative research: The case of interviews with elite informants. *Strategic Management Journal*, 40(8), 1291–1315. <https://doi.org/10.1002/smj.3015>
- Aljarrah, M., Ashraf, A., Khandakar, A., Rohouma, W., Ayari, M. A., Esmaeili, A., Butt, R., Kadampotupadeth, S., Thomas, K., Rahman, A., & Phillips, M. (2024). Environmental performance analysis of three organic waste disposal scenarios: Landfilling, composting, and EP-50. *Discover Sustainability*, 5(1), 445. <https://doi.org/10.1007/s43621-024-00614-7>
- Amrullah, S., Amin, M., & Ali, M. (2021). Converting husbandry waste into liquid organic fertilizer using probiotic consortiums (*Lactobacillus* sp., *Rhodopseudomonas* sp., *Actinomycetes* sp., *Streptomyces* sp.). *IOP Conference Series: Earth and Environmental Science*, 679(1), 012001. <https://doi.org/10.1088/1755-1315/679/1/012001>
- Bhat, M. A., Mishra, A. K., Shah, S. N., Bhat, M. A., Jan, S., Rahman, S., Baek, K.-H., & Jan, A. T. (2024). Soil and Mineral Nutrients in Plant Health: A Prospective Study of Iron and Phosphorus in the Growth and Development of Plants. *Current Issues in Molecular Biology*, 46(6), 5194–5222. <https://doi.org/10.3390/cimb46060312>
- Chen, Q., Song, Y., An, Y., Lu, Y., & Zhong, G. (2024). Soil Microorganisms: Their Role in Enhancing Crop Nutrition and Health. *Diversity*, 16(12), 734. <https://doi.org/10.3390/d16120734>
- Das, D., Riamei, M., Paul, P., Singh, N., Ingti, B., Sarkar, R. D., Rose, R., Sharma, P. L., & Paul, S. (2025). Understanding the role of soil microorganisms in alleviating hydric and edaphic stress towards sustainable agriculture. *Discover Soil*, 2(1), 47. <https://doi.org/10.1007/s44378-025-00076-x>
- De Bang, T. C., Husted, S., Laursen, K. H., Persson, D. P., & Schjoerring, J. K. (2021). The molecular-physiological functions of mineral macronutrients and their consequences for deficiency symptoms in plants. *New Phytologist*, 229(5), 2446–2469. <https://doi.org/10.1111/nph.17074>
- Desmanto, D., Susilo, E., & Parwito, P. (2024). Pengaruh Pemberian Pupuk Organik Cair (POC) Berbahan Limbah Ikan Terhadap Pertumbuhan Dan Hasil Tanaman Sawi (*Brassica juncea* L.). *SINTA Journal (Science, Technology, and Agricultural)*, 5(1), 115–124. <https://doi.org/10.37638/sinta.5.1.115-124>
- Erika Erika & Eva Gusmira. (2024). Analisis Dampak Limbah Sampah Rumah Tangga Terhadap Pencemaran Lingkungan Hidup. *Profit: Jurnal Manajemen, Bisnis Dan Akuntansi*, 3(3), 90–102. <https://doi.org/10.58192/profit.v3i3.2245>
- Esercizio, N., Lanzilli, M., Vastano, M., Landi, S., Xu, Z., Gallo, C., Nuzzo, G., Manzo, E., Fontana, A., & d'Ippolito, G. (2021). Fermentation of Biodegradable Organic Waste by the Family Thermotogaceae. *Resources*, 10(4), 34. <https://doi.org/10.3390/resources10040034>
- Gcharge, V., Ghutake, S., & Pawar, H. (2024). Valorization of Pineapple Waste for Extraction and Purification of Bromelain Enzyme. *ACS Sustainable Resource Management*, 1(11), 2439–2451. <https://doi.org/10.1021/acssusresmgt.4c00283>
- Guggisberg, S. (2022). Transparency in the activities of the Food and Agriculture Organization for sustainable fisheries. *Marine Policy*, 136, 104498. <https://doi.org/10.1016/j.marpol.2021.104498>
- Guo, H., Guan, M., Wang, Y., Li, X., Wang, H., He, C., & Chen, C. (2025). Research on the synergistic optimization of *Scutellaria baicalensis* yield, quality and soil environment by key microorganisms, driven by the combined approach of reducing chemical fertilizer usage while incorporating organic fertilizer. *Industrial Crops and Products*, 229, 121044. <https://doi.org/10.1016/j.indcrop.2025.121044>
- Hiywotu, A. M. (2025). Advancing sustainable agriculture for goal 2: Zero hunger - a comprehensive overview of practices, policies, and technologies. *Agroecology and Sustainable Food Systems*, 49(7), 1027–1055. <https://doi.org/10.1080/21683565.2025.2451344>
- Islam, M. R., Kamal, Mohd. M., Alam, M. A., Hossain, J., Soufan, W., Skalicky, M., Brestic, M., Habib-ur-Rahman, M., El Sabagh, A., & Islam, M. S. (2021).

- Physiochemical Changes of Mung Bean [*Vigna radiata* (L.) R. Wilczek] in Responses to Varying Irrigation Regimes. *Horticulturae*, 7(12), 565. <https://doi.org/10.3390/horticulturae7120565>
- Jia, Z., Giehl, R. F. H., & Von Wirén, N. (2022). Nutrient-hormone relations: Driving root plasticity in plants. *Molecular Plant*, 15(1), 86–103. <https://doi.org/10.1016/j.molp.2021.12.004>
- Kitole, F. A., Ojo, T. O., Emenike, C. U., Khumalo, N. Z., Elhindi, K. M., & Kassem, H. S. (2024). The Impact of Poor Waste Management on Public Health Initiatives in Shanty Towns in Tanzania. *Sustainability*, 16(24), 10873. <https://doi.org/10.3390/su162410873>
- Kumar, S., Kumar, S., & Mohapatra, T. (2021). Interaction Between Macro- and Micro-Nutrients in Plants. *Frontiers in Plant Science*, 12, 665583. <https://doi.org/10.3389/fpls.2021.665583>
- Lange, M., Eisenhauer, N., Sierra, C. A., Bessler, H., Engels, C., Griffiths, R. I., Mellado-Vázquez, P. G., Malik, A. A., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B. C., Trumbore, S. E., & Gleixner, G. (2015). Plant diversity increases soil microbial activity and soil carbon storage. *Nature Communications*, 6(1), 6707. <https://doi.org/10.1038/ncomms7707>
- Li, J., Yi, C., Zhang, C., Pan, F., Xie, C., Zhou, W., & Zhou, C. (2021). Effects of light quality on leaf growth and photosynthetic fluorescence of *Brasenia schreberi* seedlings. *Heliyon*, 7(1), e06082. <https://doi.org/10.1016/j.heliyon.2021.e06082>
- Maintang, Sudding, F., Asri, M., & Rauf, A. W. (2021). Application of liquid organic and inorganic fertilizer on growth and production of hybrid maize. *IOP Conference Series: Earth and Environmental Science*, 648(1), 012140. <https://doi.org/10.1088/1755-1315/648/1/012140>
- Martínez-Chávez, L. A., Hernández-Ramírez, M. Y., Feregrino-Pérez, A. A., & Esquivel Escalante, K. (2024). Cutting-Edge Strategies to Enhance Bioactive Compound Production in Plants: Potential Value of Integration of Elicitation, Metabolic Engineering, and Green Nanotechnology. *Agronomy*, 14(12), 2822. <https://doi.org/10.3390/agronomy14122822>
- Marzouk, S. H., Kwaslema, D. R., Omar, M. M., & Mohamed, S. H. (2025). "Harnessing the power of soil microbes: Their dual impact in integrated nutrient management and mediating climate stress for sustainable rice crop production" A systematic review. *Heliyon*, 11(1), e41158. <https://doi.org/10.1016/j.heliyon.2024.e41158>
- Mgeni, S. T., Mero, H. R., Mtashobya, L. A., & Emmanuel, J. K. (2024). The prospect of fruit wastes in bioethanol production: A review. *Heliyon*, 10(19), e38776. <https://doi.org/10.1016/j.heliyon.2024.e38776>
- Mildaziene, V., Ivankov, A., Sera, B., & Baniulis, D. (2022). Biochemical and Physiological Plant Processes Affected by Seed Treatment with Non-Thermal Plasma. *Plants*, 11(7), 856. <https://doi.org/10.3390/plants11070856>
- Muqsit, F. A., Setiadi, R., & Lo, A. (2024). Waste Management in Heritage Tourism Area: Perspectives from Visitors and Waste Management Operators. *The Journal of Indonesia Sustainable Development Planning*, 5(1), 15–26. <https://doi.org/10.46456/jisdep.v5i1.524>
- Nanda, Lubis, R. A., Mukhlis, Nasution, F. E., & Sipahutar, L. W. (2025). Integrasi Evaluasi Eksperimental dan Analisis Bibliometrik Photosynthetic Bacteria dan Jakaba sebagai Bioaktivator Pertanian Organik. *Jurnal Penelitian Pendidikan IPA*, 11(7), 142–151. <https://doi.org/10.29303/jppipa.v11i7.11789>
- Paz, S. (2024). Climate change: A driver of increasing vector-borne disease transmission in non-endemic areas. *PLOS Medicine*, 21(4), e1004382. <https://doi.org/10.1371/journal.pmed.1004382>
- Pompelli, M. F., Jarma-Orozco, A., & Rodriguez-Páez, L. A. (2023). Imbibition and Germination of Seeds with Economic and Ecological Interest: Physical and Biochemical Factors Involved. *Sustainability*, 15(6), 5394. <https://doi.org/10.3390/su15065394>
- Rachman, I. A., Umasugi, B., Aji, K., Hakim, N. F. A., Sofyan, A., & Hasan, A. D. A. (2025). Effect of eco-enzyme application on soil nutrient and plant productivity of green mustard-peanut in inceptisol. *Kultivasi*, 24(2), 196–205. <https://doi.org/10.24198/kultivasi.v24i2.64591>
- Sherzad, Z., Nawakht, N. A., & Sherzad, F. (2025). Plant growth-promoting endophytic bacteria: A sustainable solution for climate change and environmental stresses in agriculture. *Discover Applied Sciences*, 7(8), 894. <https://doi.org/10.1007/s42452-025-07123-w>
- Suman, J., Rakshit, A., Ogireddy, S. D., Singh, S., Gupta, C., & Chandrakala, J. (2022). Microbiome as a Key Player in Sustainable Agriculture and Human Health. *Frontiers in Soil Science*, 2, 821589. <https://doi.org/10.3389/fsoil.2022.821589>
- Sun, Q., Zhang, Q., Huang, Z., Wei, C., Li, Y., & Xu, H. (2024). Effect of Organic Fertilizer Application on Microbial Community Regulation and Pollutant Accumulation in Typical Red Soil in South China. *Agronomy*, 14(9), 2150. <https://doi.org/10.3390/agronomy14092150>
- Syllistiana, L. (2025). Process of Making Liquid Organic Fertilizer in Biotechnology Material. *International Journal of Science Education and Science*, 2(2), 74–77. <https://doi.org/10.56566/ijses.v2i2.225>

- Waheed, M., Mutahir Abbas, & Arif, S. H. (2023). Utilizing Internet of Thing for Construction Waste Management in Pakistan. *Journal Of Digital Learning And Distance Education*, 2(3), 506–512. <https://doi.org/10.56778/jdlde.v2i3.134>
- Wawrzyniak, M. K., Michalak, M., & Chmielarz, P. (2020). Effect of different conditions of storage on seed viability and seedling growth of six European wild fruit woody plants. *Annals of Forest Science*, 77(2), 58. <https://doi.org/10.1007/s13595-020-00963-z>
- Wei, X., Xie, B., Wan, C., Song, R., Zhong, W., Xin, S., & Song, K. (2024). Enhancing Soil Health and Plant Growth through Microbial Fertilizers: Mechanisms, Benefits, and Sustainable Agricultural Practices. *Agronomy*, 14(3), 609. <https://doi.org/10.3390/agronomy14030609>
- Yan, J., Mackay, A. J., & Stone, C. M. (2024). Dynamics of invasive mosquitoes: Introduction pathways, limiting factors, and their potential role in vector-borne pathogen transmission. *Frontiers in Tropical Diseases*, 5, 1503120. <https://doi.org/10.3389/fitd.2024.1503120>
- Yoneyama, T. (2021). Iron delivery to the growing leaves associated with leaf chlorosis in mugineic acid family phytosiderophores-generating graminaceous crops. *Soil Science and Plant Nutrition*, 67(4), 415–426. <https://doi.org/10.1080/00380768.2021.1947735>
- Zhou, Z., Zhang, S., Jiang, N., Xiu, W., Zhao, J., & Yang, D. (2022). Effects of organic fertilizer incorporation practices on crops yield, soil quality, and soil fauna feeding activity in the wheat-maize rotation system. *Frontiers in Environmental Science*, 10, 1058071. <https://doi.org/10.3389/fenvs.2022.1058071>