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Application of Microbial Consortium Biofertilizer on Growth Performance and Soil Properties of Red Amaranth (*Amaranthus tricolor* L.) in Tropical Environments

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Abstract. *Red amaranth (Amaranthus tricolor L.) is an important leafy vegetable for food security in tropical regions, but its productivity is often limited by high temperatures and irregular rainfall. This study evaluated the effects of microbial consortium biofertilizers on the growth and soil nutrient status of red amaranth under tropical conditions. The experiment used a Completely Randomized Design (CRD) with three treatments—P0 (control), P1 (bacterial consortium), and P2 (fungal consortium)—each replicated eight times. Data were analyzed using Duncan's Multiple Range Test (DMRT) at the 5% level, and relationships among variables were assessed using Principal Component Analysis (PCA). Treatment P2 (fungal consortium) was associated with higher vegetative growth parameters, including plant height (10.8 cm), number of leaves (5.5), and leaf area (22.4 cm²). In contrast, P1 (bacterial consortium) resulted in greater biomass accumulation, with fresh weight (10.04 g) and dry weight (6.71 g). Soil nitrogen (1.86%) was higher in P2, while soil pH remained within a slightly acidic range suitable for plant growth across all treatments. PCA showed clear separation among treatments, with P2 associated with vegetative growth variables and P1 linked to biomass-related parameters. Unlike previous studies focused mainly on growth responses, this study integrates soil nutrient dynamics and multivariate analysis to reveal distinct patterns of vegetative dominance and biomass allocation under microbial consortium biofertilization. Fungal consortia primarily enhanced vegetative development, whereas bacterial consortia favored biomass accumulation. These results suggest that microbial consortium composition can be tailored to specific production objectives in leafy vegetable systems. However, further validation under diverse environmental conditions and across multiple growing seasons is needed before broader agronomic application.*
Keywords: *biofertilizer; microbial consortium; growth; red amaranth; tropical environment.*

Type of the Paper: Regular Article.

1. Introduction

Agricultural systems worldwide face growing pressure from environmental degradation, climate change, and heavy reliance on synthetic chemical inputs—all of which harm soil health and undermine the long-term sustainability of food production [1]. In tropical regions, high temperatures, irregular rainfall, and declining soil fertility are major constraints on horticultural crop productivity [2]. Intensive use of chemical fertilizers may raise yields in the short term, but prolonged application can degrade soil quality, disrupt soil microbial balance, and increase greenhouse gas emissions [3]. Sustainable agricultural approaches that rely on biological resources

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have therefore become a global priority [4].

Similar challenges occur in Indonesia, especially in vegetable production systems where soil fertility decline and environmental pressure are common [5]. Red amaranth (*Amaranthus tricolor* L.) is an important leafy vegetable due to its high nutritional value, short growth cycle, and stable market demand [6]. However, its productivity is often limited by nutrient deficiencies and abiotic stresses, including high temperatures and inconsistent water availability in tropical environments [7]. Efforts to increase red amaranth production still rely heavily on inorganic fertilizers, which, despite their immediate effectiveness, may reduce soil quality and raise production costs over time [8].

Biofertilizers containing microbial inoculants have emerged as a promising alternative for improving plant nutrition and crop performance. Biofertilizers consist of living microorganisms capable of improving nutrient availability and stimulating plant growth through mechanisms such as nitrogen fixation, phosphate solubilization, and phytohormone production [9]. Microbial consortia, which combine multiple beneficial microorganisms, often exhibit synergistic effects that surpass the effectiveness of single-strain inoculants [10]. These consortia have been reported to enhance nutrient uptake, improve soil structure, and increase plant tolerance to environmental stress through mechanisms such as systemic resistance induction [11]. Despite growing evidence on microbial biofertilizers in leafy vegetables, comparative data differentiating bacterial and fungal consortia—in terms of vegetative dominance versus biomass allocation under tropical stress—remain limited, particularly for *Amaranthus tricolor*. This gap constrains the optimization of biofertilizer strategies tailored to specific production objectives.

Unlike previous studies that mainly report growth responses to single-strain or undefined microbial inoculants, this study directly compares a bacterial consortium (Bacillus mycoides, B. paramycoides, and B. inaquosorum) with a fungal consortium (Penicillium citrinum and Phanerodontia chrysosporium) in red amaranth under tropical conditions. By integrating growth performance, soil nutrient status (N, P, K), and multivariate analysis (PCA), this study reveals a functional trade-off: the fungal consortium favored vegetative development, whereas the bacterial consortium favored biomass accumulation. This distinction has not been previously documented for Amaranthus tricolor and provides a basis for tailoring consortium composition to specific production objectives.

Although several studies have shown positive effects of microbial consortia on the growth of leafy vegetables, research on their application to red amaranth—particularly concerning plant resistance to tropical environmental stress—remains limited. Most existing studies focus primarily on growth enhancement without evaluating plant resilience under abiotic stress conditions [12]. Research that integrates both growth performance and stress resistance is essential to support

sustainable vegetable production systems. Accordingly, this study evaluates the effects of microbial consortium biofertilizers on the growth and resistance of red amaranth (*Amaranthus tricolor* L.) under tropical environmental conditions.

2. Materials and Methods

2.1 Place and Time

This research was conducted over two months, from October to November 2025, at the experimental field of Universitas Negeri Padang, Sijunjung Campus, which is geographically located at coordinates −0.664693° S and 100.927202° E. The site has relatively uniform environmental conditions, which supports consistent data collection.

2.2 Materials and Tools

The materials used in this study were red amaranth seeds, homogeneous soil media, water, and a microbial consortium biofertilizer applied at a dose of 10 mL per treatment: P0 (Control), P1 (bacterial consortium of *Bacillus mycoides*, *Bacillus paramycoides*, and *Bacillus inaquosorum*), and P2 (*fungal consortium of Penicillium citrinum* and *Phanerodontia chrysosporium*). Each consortium was dissolved in 1 L of distilled water in an Erlenmeyer flask before application to the plants. The tools used were a hoe for preparing three beds measuring 2 × 3 m, buckets for watering, a ruler (cm), a digital scale, treatment labels, stationery, an NPK tester, a pH meter, and a thermometer.

2.3 Research Design

This study used a Completely Randomized Design (CRD) with treatments: P0 (control), P1 (bacterial consortium), and P2 (fungal consortium). Each treatment was replicated eight times, giving a total of 24 experimental units [13]. All units were treated identically according to the research protocol to ensure consistent observations.

2.4 Research Procedure

2.4.1 Biofertilizer Preparation

Biofertilizer preparation began with a liquid medium of carboxymethyl cellulose (CMC) as a substrate for microbial growth. The medium was prepared by dissolving 100 mL of distilled water, 1 g of CMC, 2 g of agar, and 1 g of peptone, then heating until homogeneous. The medium was sterilized in an autoclave at 121 °C for 15 min to prevent contamination. After sterilization, the medium was cooled to room temperature. The bacterial and fungal consortia were each inoculated at 1 mL into 100 mL of sterile medium. The mixture was then fermented for 7 d at room temperature to allow the microbial population to reach optimal activity. The biofertilizer was then ready for application at planting.

2.4.2. Land Preparation

The experimental plots were manually cultivated with a hoe to loosen the soil before planting. Three beds, each measuring 2 × 3 m, were prepared according to the experimental design. Tillage aimed to improve aeration, increase soil porosity, and facilitate root penetration during growth.

2.4.3. Planting and Application of Biofertilizer

Red amaranth seeds were sown directly at predetermined points following a Completely Randomized Design (CRD). The first biofertilizer application was performed during the initial watering at planting to ensure microbial availability from early germination. The second application was carried out 7 days after planting (DAP) according to treatment: P0 (no biofertilizer), P1 (bacterial consortium), and P2 (fungal consortium). The biofertilizer dose was adjusted to the concentration of the fermentation product and applied evenly to each experimental unit.

2.4.4. Plant Maintenance

Plants were watered twice daily, in the morning and evening, to maintain optimal soil moisture. Weeding was done manually to prevent competition for nutrients and light. Pest attacks were monitored, and control measures were applied mechanically without chemical pesticides to avoid disrupting biofertilizer microbial activity.

2.4.5. Harvesting

Plants were harvested at the end of the fifth week after planting, when they had reached the optimal growth phase for biomass evaluation. Each plant was carefully uprooted to preserve root biomass. Fresh and dry weights were recorded using a high-precision digital scale.

2.5 Observation Variables

2.5.1. Plant observation

Plant growth variables were height, number of leaves, visual condition, fresh weight, and dry weight. Plant height was measured with a ruler (1 cm precision) from the base of the stem to the highest growth point. Leaf area was measured using a screw micrometer (1 mm precision). Only fully opened leaves were counted. Fresh weight was determined by weighing all plant parts with a digital scale immediately after harvest at the end of the fifth week.

2.5.2. Observation of Soil Nutrients

Soil nitrogen (N), phosphorus (P), and potassium (K) were analyzed using a Digital Soil NPK Rapid Tester. This portable, sensor-based method provides rapid in situ estimates of soil nutrient status and enables real-time monitoring, making it suitable for timely soil fertility assessment in precision agriculture [13]. Soil samples were mixed with distilled water at a 1:2 (v/v) ratio and stirred until homogeneous. The sensor probe was inserted vertically into the

suspension, and readings were recorded after approximately 10 seconds, once stable values were obtained. Measurements were repeated three times per treatment to ensure consistency. The device has a detection range of approximately 0–1999 mg kg^{-1}, with accuracy influenced by soil moisture, texture, and environmental conditions. It therefore provides semi-quantitative estimates rather than absolute values. Compared with standard laboratory methods such as Kjeldahl digestion for nitrogen, Olsen or Bray extraction for phosphorus, and atomic absorption spectrometry (AAS) for potassium, this method has lower precision. The values should therefore be interpreted as indicative and are intended primarily for comparative evaluation among treatments, while offering the advantage of rapid, real-time field assessment.

2.6. Data Analysis

Data were analyzed using STAR (Statistical Tool for Agricultural Research). When significant differences were detected among treatments, Duncan's Multiple Range Test (DMRT) at a 5% significance level was used to separate treatment means. Principal Component Analysis (PCA) was also performed to evaluate relationships between microbial biofertilizer characteristics and red amaranth growth responses. PCA was conducted in RStudio [14].

3. Results and Discussion

3.1. Results

3.1.1. Characterization of Red Amaranth Growth Based on Biofertilizer Treatment

Biofertilizers with different microbial compositions produced varied growth responses in red amaranth. Growth characteristics were evaluated to assess differences among treatments. The parameters measured were plant height, number of leaves, leaf area, plant condition score, and fresh and dry weight. Mean values for each parameter are presented in Table 1.

Table 1. Growth Performance of Red Amaranth (*Amaranthus tricolor* L.) Under Different Microbial Consortium Biofertilizer Treatments.

Treatment	Plant Height (cm)	Number of leaves	Leaf Area (cm^2)	Plant Conditions (Score)	Wet Weight (g)	Dry Weight (g)
Control (P0)	7.7^{c}	5.1^{b}	13.8^{c}	3.9	5.43^{c}	2.74^{c}
Kb (P1)	9.7^{b}	4.6^{c}	20.3^{b}	4.0	10.04^{a}	6.71^{a}
Kj (P2)	10.8^{a}	5.5^{a}	22.4^{a}	4.0	9.36^{b}	4.98^{b}

Note: Values in each column followed by the same letter are not significantly different based on DMRT at the 5% level ($p \leq 0.05$). Plant condition score: 1 = very bad; 2 = bad; 3 = medium/sufficient; 4 = good; 5 = excellent.

The highest plant height was recorded in treatment P2 (10.8 cm), followed by P1 (9.7 cm), while the control (P0) had the lowest value (7.7 cm). The number of leaves did not follow the same trend as plant height. Treatment P2 produced the highest number of leaves (5.5), followed by P0 (5.1), whereas P1 had the lowest (4.6 leaves). Leaf area was significantly higher in the biofertilizer treatments: P1 and P2 recorded 20.3 cm^2 and 22.4 cm^2, respectively, compared to 13.8 cm^2 in the control. Plant condition scores ranged from 3.9 to 4.0 across all treatments. Fresh and dry weight

varied among treatments. The highest fresh weight was recorded in P1 (10.04 g), followed by P2 (9.36 g) and P0 (5.43 g). Similarly, dry weight was highest in P1 (6.71 g), followed by P2 (4.98 g) and P0 (2.74 g).

3.1.2. Environmental Parameters

Environmental parameters, including humidity, soil pH, and temperature, were measured during the experiment. Mean values are presented in Table 2.

Table 2. Environmental parameters associated with red amaranth (*Amaranthus tricolor* L.) under different microbial consortium biofertilizer treatments.

Treatment	Humidity (%)	pH	Temperature (°C)
Control (P0)	45.20	6.04^{c}	31.04^{a}
Kb (P1)	46.80	6.16^{b}	30.72^{a}
Kj (P2)	45.20	6.38^{a}	30.23^{b}

Note: Values in each column followed by the same letter are not significantly different based on DMRT at the 5% level ($p \leq 0.05$). Humidity levels: 0–20% (very dry); 21–40% (dry); 41–60% (moderate); 61–80% (high humidity); 81–100% (very wet/saturated).

Humidity ranged from 45.20 % to 46.80 %, indicating relatively stable moisture conditions across treatments. Treatment P1 recorded the highest humidity (46.80 %), while P0 and P2 showed identical values (45.20 %). Soil pH varied among treatments, with the highest value in P2 (6.38), followed by P1 (6.16) and P0 (6.04). Temperature ranged from 30.23°C to 31.04°C, with P0 recording the highest temperature and P2 the lowest. Treatments P0 and P1 shared the same statistical grouping for temperature.

DMRT indicated statistically significant differences in soil pH among treatments; however, these differences should be interpreted with caution. All recorded pH values (P0 = 6.04, P1 = 6.16, and P2 = 6.38) fell within the “slightly acid” range (pH 5.5-6.5), and none reached the “neutral” category (pH 6.6–7.5). The observed differences therefore reflect variation in magnitude rather than a shift in soil reaction class.

Although statistically significant, these differences did not result in a change in soil pH classification. All treatments also had pH values within or close to the optimal range for *Amaranthus tricolor* growth (approximately pH 6.0–7.0), indicating that soil pH was not a limiting factor for plant performance in this study.

3.1.3. Soil Nutrient Content (N, P, K)

Soil nitrogen (N), phosphorus (P), and potassium (K) differed among treatments Table 3.

Table 3. Nutrient contents (N, P, and K) of red amaranth (*Amaranthus tricolor* L.) planting media under different microbial consortium biofertilizer treatments.

Treatment	Nitrogen (%)	Phosphorus (%)	Potassium (%)
P0	1.53^{b}	1.76^{b}	3.93^{b}
P1	1.3^{c}	1.5^{c}	3.43^{c}
P2	1.86^{a}	2.2^{a}	5.0^{a}

Note: Values in each column followed by the same letter are not significantly different based on the DMRT at the 5 % level ($p \leq 0.05$).

Treatment P2 had the highest nutrient content, with nitrogen at 1.86 %, phosphorus at 2.20 %, and potassium at 5.00 %. Treatment P0 recorded intermediate values (1.53 %, 1.76%, and 3.93 %), while P1 had the lowest values (1.30 %, 1.50 %, and 3.43 %).

3.1.4. Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was performed to evaluate the relationships between microbial biofertilizer treatments and plant growth variables. The PCA results showed variation among treatments based on plant growth parameters. The scree plot (Fig. 1) presents the contribution of principal components, with PC1 and PC2 explaining the majority of the total variance.

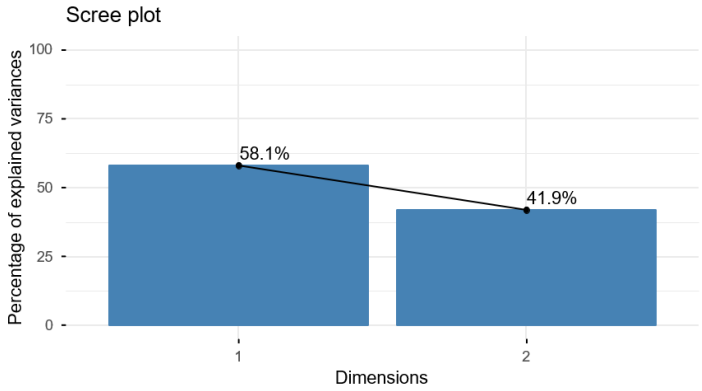


Fig 1. Scree Plot PCA.

The PCA biplot (Fig. 2) illustrates the distribution of treatments and their associations with measured variables. Treatment P2 was closer to plant height (10.8 cm), number of leaves (5.5), and leaf area (22.4 cm²), whereas treatment P1 was positioned closer to fresh weight (10.04 g) and dry weight (6.71 g). The control treatment (P0) was separated from both P1 and P2 and associated with lower values across all variables.

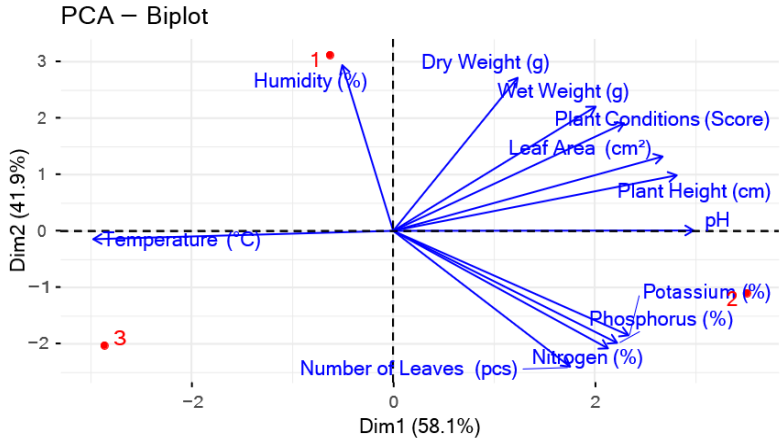


Fig 2. PCA biplot.

The variable contribution plot (Fig. 3) shows that plant height, number of leaves, and leaf area contributed more strongly to PC1, while fresh and dry weight contributed primarily to PC2.

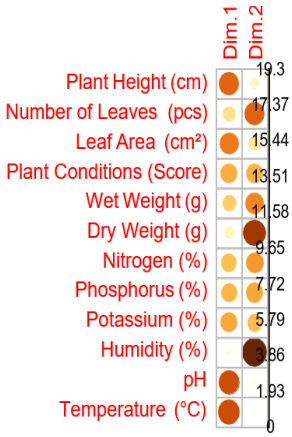


Fig 3. PCA variable contribution plot.

The PCA scatter plot (Fig. 4) further demonstrates the separation of treatments along the principal component axes. Treatments P1 and P2 were on the positive side of PC1, whereas the control (P0) was positioned on the negative side, reflecting lower values of growth parameters.

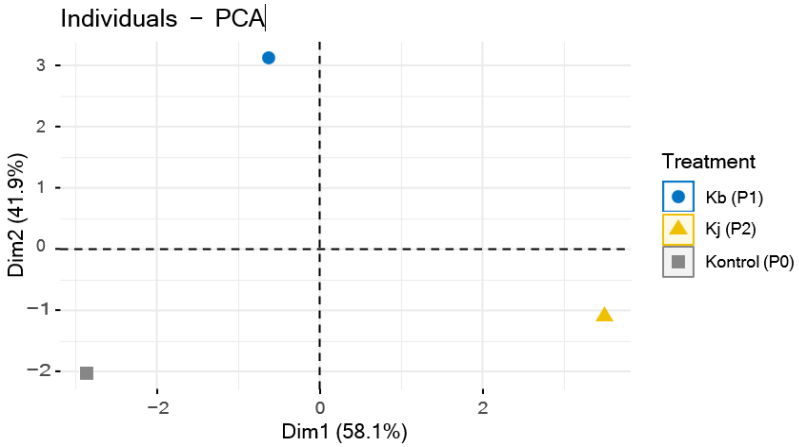


Fig 4. Scatter plot of isolates based on PCA.

The correlation plot between microbial biofertilizer variables and plant growth parameters (Fig. 5) shows the association patterns among variables included in the analysis.

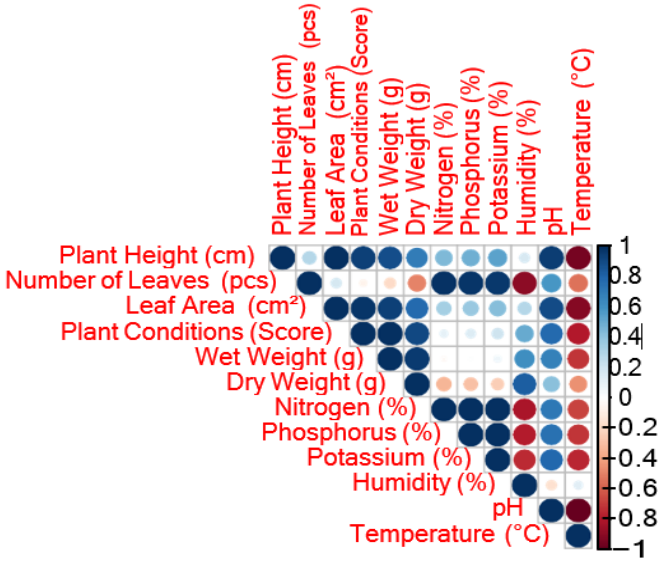


Fig 5. Correlation between local microbial biofertilizer variables and red amaranth growth.

3.2. Discussion

Variation in N, P, and K among treatments led to differences in nutrient availability that influenced the physiological response of red amaranth. Treatment P2 (fungal consortium) had the highest nitrogen (1.86%), phosphorus (2.20%), and potassium content, corresponding to the greatest plant height, leaf number, and leaf area. This pattern is consistent with previous studies showing that increased nitrogen availability enhances plant height, leaf development, and leaf expansion through improved photosynthetic activity [15,16]. Phosphorus plays a key role in ATP synthesis and cell division, while potassium contributes to stomatal regulation and assimilate transport, all of which support vegetative growth [17]. In contrast, treatment P1 (bacterial consortium) produced the highest fresh weight (10.04 g) and dry weight (6.71 g), although its vegetative parameters were lower than those of P2. This pattern indicates greater biomass accumulation under P1. Similar findings have been reported where organic or microbial amendments promote biomass production even when morphological traits are not maximized [18,19].

Differences in nutrient allocation between plant organs may reflect adaptive strategies in which assimilates are directed toward structural development and storage [20,21]. The contrasting responses between P1 and P2 highlight a functional trade-off between vegetative expansion and biomass accumulation. While P2 promoted greater vegetative development, P1 was associated with higher biomass production, which is in line with findings that fertilization strategies can differentially affect growth and biomass yield [22,23]. This suggests that differences in microbial consortium composition may influence carbon allocation strategies, directing assimilates either toward morphological expansion or biomass accumulation rather than uniformly enhancing all growth parameters [24].

Environmental factors such as light intensity and relative humidity were similar across treatments and were therefore not considered major drivers of growth differences. Although P2 showed slightly higher pH and lower temperature, these factors should be interpreted with caution, as all treatments remained within comparable environmental ranges. This is consistent with studies showing that minor environmental variations within optimal ranges do not significantly alter plant growth outcomes [25].

Plant condition scores were relatively uniform (3.9–4.0), indicating that all treatments maintained plants in generally good condition. This finding is consistent with previous studies showing that organic and biological fertilizers can sustain plant health under varying growth responses [26].

Overall, treatment P2 was associated with improved vegetative growth parameters, whereas P1 showed greater biomass accumulation. The control (P0) consistently had the lowest values

across measured parameters, in agreement with previous reports highlighting the importance of nutrient input for optimizing plant growth and yield [23,26]. These results suggest that microbial biofertilizer application can be adjusted based on production objectives, with P1 favoring biomass yield and P2 supporting vegetative development [24].

4. Conclusions

Microbial consortium biofertilizers influenced the growth performance of red amaranth (*Amaranthus tricolor* L.) under the conditions of this study. Treatments differed in nutrient availability and plant growth responses: P2 (fungal consortium) was associated with higher vegetative growth parameters, while P1 (bacterial consortium) was associated with greater biomass accumulation. These findings provide a basis for targeted biofertilizer application, where fungal consortia may support canopy development and bacterial consortia may optimize biomass production in leafy vegetable systems. However, this study was conducted under controlled conditions over a limited duration and at a single site. Further research across different locations, soil types, and growing seasons is therefore needed to validate these results before broader agronomic recommendations can be made.

Abbreviations

STAR	Statistical Tool for Agricultural Research
DMRT	Duncan Multiple Range Test
PCA	Principal Component Analysis
P0	Control treatment
P1	Bacterial consortium biofertilizer
P2	Fungal consortium biofertilizer
Kb	Bacterial consortium (treatment P1)
Kj	Fungal consortium (treatment P2)
Pcs	pieces (unit for number of leaves)

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. All datasets, including raw measurements, processed data, and analysis outputs, can be provided for academic and research purposes.

CRediT Authorship Contribution Statement

Santi Diana Putri: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing original draft, Writing, review and editing. **Hermansah**: Supervision, Conceptualization, Methodology, Validation, Project administration, Funding acquisition, Writing, review and editing. **Agustian**: Methodology, Resources, Validation, Formal analysis, Writing, review and editing. **Nurmiati**: Supervision, Validation, Resources, Writing, review and editing.

Declaration of Competing Interest

The authors of this manuscript declare no conflict of interest or competing interest.

Declaration of Use of AI in the Writing Process

The author(s) used Microsoft Copilot during the preparation of this manuscript to improve grammar, refine sentence structure, and enhance clarity of expression. After using the tool/service, the author(s) carefully reviewed, validated, and edited the content, and take full responsibility for the accuracy, integrity, and originality of the final manuscript.

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References

[1] Lacerda VR, Costa BNS, Li X. Sustainable practices in tropical horticulture: a path to resilient agricultural systems. Technology in Horticulture 2025;5:e004. https://doi.org/10.37155/tih-0024-0033. https://www.maxapress.com/article/doi/10.48130/tihort-0024-0033

[2] wu G, Yang S, Luan C, Wu Q, Lin L, Li X, et al. Partial organic substitution for synthetic fertilizer improves soil fertility and crop yields while mitigating N2O emissions in wheat-maize rotation system. European Journal of Agronomy 2024;152:127003. https://www.sciencedirect.com/science/article/abs/pii/S1161030123003453

[3] Teren-Samaniego K, Robles-Parra JM, Vargas-Arispuro I, Martinez-Tellez MA, Garza-Lagler MC, Felix-Gurrlola D, et al. Agroecology and sustainable agriculture: Conceptual challenges and opportunities—A systematic literature review. Sustainability 2025;17:1805. https://doi.org/10.3390/su17051805.

[4] Dewi T, Widyati E, Maftu'ah E, Irianto RSB, Hartatik SE, Susilo A, et al. Protecting agricultural soils from contamination to produce healthy foods: Policies and practices in Indonesia. Producing Healthy Food with Healthy Soils, Cham: Springer; 2025;33-57. https://doi.org/10.1007/978-3-031-82536-1_4.

[5] Segura-jimenez ME, Jacona-velazquez DA. Amaranthus spp.: A multifunctional crop at the nexus of nutrition, health, and sustainable innovation. Journal of Agriculture and Food Research 2025;9:100933. https://www.sciencedirect.com/science/article/pii/S2666154325006933

[6] Sarker U, Oba S, Ullah R, Bari A, Ercisli S, Skrovankova, et al. Nutritional and bioactive properties and antioxidant potential of Amaranthus tricolor, A. lividus, A. viridis, and A. spinosus leafy vegetables. Heliyon 2024;10:e30453. https://www.cell.com/heliyon/fulltext/S2405-8440(24)06484-3

[7] Susanti WI, Cholidah SN, Agus F. Agroecological nutrient management strategy for attaining sustainable rice self-sufficiency in Indonesia. Sustainability 2024;16:845. https://doi.org/10.3390/su16020845.

[8] Shahzad M, Hayat R, Mujtaba G, Rehman WU, Nadeem M. Biofertilizers in sustainable agriculture: Mechanisms, applications, and future prospects. Discover Agriculture 2025;3:318. https://doi.org/10.1007/s44279-025-00318-0.

[9] Marghoob MU, Nawaz A, Ahmad M, Waheed MQ, Khan MH, Imtiaz M, et al. Assessment of halotolerant bacterial and fungal consortia for augmentation of wheat in saline soils. Frontiers in Microbiology 2023;14:1207784. https://doi.org/https://doi.org/10.3389/fmicb.2023.1207784 https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1207784/full

[10] Timofeeva AM, Galyamova MR, Sedykh SE. Plant growth-promoting soil bacteria: Nitrogen fixation, phosphate solubilization, siderophore production, and other biological activities. Plants 2023;12:4074. https://doi.org/10.3390/plants12244074.

[11] Jayathilake KMPI, Manage PM, Idroos FS. Synergistic effect of Bacillus spp. and Aspergillus spp. as biofertilizers spray on nutrient uptake and growth enhancement in lettuce (Lactuca sativa) and radish (Raphanus sativus): Impact of biofertilizer on soil fertility and sustainable agriculture. Journal of Microbiology, Biotechnology and Food Sciences 2025;14:e12404. https://doi.org/10.55251/jmbfs.12404 https://office2.jmbfs.org/index.php/JMBFS/article/view/12404/3861

[12] Datta M, Godan TK, Halder SK, Mukherjee R. Insights into plant beneficial microorganism-triggered induced systemic resistance. Current Research in Microbial Sciences 2023;6:100189. https://doi.org/10.1016/j.crmicr.2023.100189 https://www.researchgate.net/publication/368892322_Insights_into_plant_beneficial_microorganism-triggered_induced_systemic_resistance

[13] Prado K, Holland BL, Gardener BM, Lundquist PK, Santiago JP, VanBuren R, et al. Building climate-resilient crops: genetic, environmental, and technological strategies for heat and drought stress tolerance. Journal of Experimental Botany 2025;76:4395–4413. https://doi.org/https://doi.org/10.1093/jxb/eraf111 https://pubmed.ncbi.nlm.nih.gov/40062368/

[14] Nirankar, Mandal J, Parveen A, Kumar A, Kumar Y, Singh SK. Effect of Various Sources of Nitrogen on Growth, Yield, and Quality in Vegetable Amaranthus (Amaranthus tricolor L.). Eco Env & Cons 2024;30:1618–22. https://www.envirobiotechjournals.com/EEC/Vol30Issue42024/EEC-26_20250106_065553.pdf

[15] Sarker HMMU, Khatun K, Mostarin T, Akter M, Alamin M, Hossain N, et al. Optimizing Nitrogen and Phosphorus Application for the Growth and Seed Yield of Katwa Amaranth (Amaranthus spp.). Asian Journal of Advances in Agricultural Research 2025;25. https://journalajaar.com/index.php/AJAAR/article/view/692

[16] Li K, Liu DN, Li LY, Gao Y, Gao WJ, Chen BW, et al. Effects of nitrogen application amount on nitrogen distribution and photosynthesis in tea leaves. Front Plant Sci 2025;16:1575317. https://doi.org/10.3389/fpls.2025.1575317.

[17] Liu Y, Gao J, Zhao Y, Fu Y, Yan B, Wan X, et al. Effects of different phosphorus and potassium supply on the root architecture, phosphorus and potassium uptake, and utilization efficiency of hydroponic rice. Sci Rep 2024;14:21178. https://doi.org/10.1038/s41598-024-72287-1.

[18] Ramangoele M, Mhlontlo S, Silwana T, Celliers R, Kubheka B. Effect of organic and inorganic fertilization on the growth and yield of two Amaranthus accessions. Afr J Agric Res 2024;21:56–65. https://www.researchgate.net/publication/391529656_Effect_of_organic_and_inorganic_fertilization_on_the_growth_and_yield_of_two_Amaranthus_accessions

[19] Seton WEE, Hounkpatin ASY, Bokossa HKJ, Hounsou S. Evaluation of the Effectiveness of a Biodegradable Organic Fertilizer Based on Neem (Azadirachta indica) 'BioNeem+' on the Agronomic Performance of Amaranth (Amaranthus cruentus) Cultivated in the Municipality of Abomey-Calavi. Agricultural Sciences 2025;16. https://www.scirp.org/journal/paperinformation?paperid=146274

[20] Garg K, Dhar S, Sharma VK, Azman EZ, Maeena RP, Hashim M, et al. Optimizing agricultural sustainability: Enriched organic formulations for growth, yield, and soil quality in a multi-crop system. Front Plant Sci 2024;15:1398083. https://doi.org/10.3389/fpls.2024.1398083.

[21] Xing Y, Zhang X, Wang X. Enhancing soil health and crop yields through water-fertilizer coupling technology. Front Sustain Food Syst 2024;8:1494819. https://doi.org/10.3389/fsufs.2024.1494819.

[22] Yang N, Zohner CM, Croether TW, Feng J, Wu J, Chen X, et al. Leaf economic strategies drive global variation in phosphorus stimulation of terrestrial plant production. Nat Commun 2025;16:5427. https://doi.org/10.1038/s41467-025-60633-4.

[23] Ortikov TK, Shoniyozov BK, Makhmatmurodov AU, Abdurakhimov MK, Sharifov KF, Shavkatova ZS, et al. Effect of fertilizers on biomass and productivity of amaranth on sierozem meadow soils of the Zeravshan valley of Uzbekistan. Plant Science Today 2025;12. https://doi.org/10.14719/pst.9124 https://doi.org/10.14719/pst.9124

[24] Yadav S, Jangu R, Malviya S, Prajapati J, Das K, Asati KP. Integrated Nutrient Management: A Pathway to Enhanced Growth and Yield in Amaranthus tricolor L. J Adv Biol Biotechnol 2024;27:885–92. https://journaljabb.com/index.php/JABB/article/view/1048

[25] V G, Anitha D. Effect of different organic fertilizers on the growth of Amaranthus tricolor (L.). International Journal of Pharmacognosy and Phytochemical Research 2018;10:363–6. https://impactfactor.org/PDF/IJPPR/10/IJPPR,Vol10,Issue12,Article1.pdf

[26] Mohil P, Jain U. Influence of Inorganic and Organic Fertilizers on Biomass Production of Amaranthus sp. Eur J Exp Biol 2016;6:33–7. https://www.primescholars.com/articles/influence-of-inorganic-and-organic-fertilizers-on-biomass-production-of-iamaranthusi-sp.pdf