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Production of Freshwater Fish Powder Fertilizer and Evaluating its Efficacy to Eggplant (Solanum Melongena L.)

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Abstract: *This study evaluated the effects of freshwater fish powder fertilizer (FFPF) applied at different basal and side-dress rates on the growth, yield, and post-harvest soil properties of eggplant (Solanum melongena L.). Four treatments were tested in a completely randomized design with four replicates per treatment: T1 (10 g basal + 10 g side-dress), T2 (15 g basal + 10 g side-dress), T3 (20 g basal + 10 g side-dress), and T4 (unfertilized control).*

Results showed that FFPF significantly enhanced vegetative growth parameters over five weeks. Plants under T3 consistently recorded the highest means for plant height, leaf number, stem diameter, and lateral branch number, followed by T2 and T1, while the control (T4) had the lowest performance. Significant treatment and time interactions indicated increasing divergence between fertilized and unfertilized plants over time. Yield analysis across eight harvests revealed significant treatment effects on fruit length, marketable fruit weight, and total yield, with T3 generally outperforming the control. However, reproductive timing traits, including days to 50% inflorescence and first harvest, were not significantly affected by treatment.

Post-harvest soil analysis showed significant changes in soil chemical properties. Soil pH decreased across treatments, with the greatest reduction observed in T1. Soil nitrogen declined in all treatments, with the highest decrease in T2. In contrast, soil phosphorus and potassium increased after harvest, with T3 showing the greatest phosphorus improvement. Overall, the findings suggest that higher rates of FFPF, particularly T3, improve eggplant growth and yield while also influencing soil nutrient dynamics, although with some indications of soil acidification and nitrogen depletion..

Keywords: Production, Freshwater Fish Powder Fertilizer, Nutrient, Evaluation, Effects, Basal application, Side-dress application, Growth, Yield, Eggplant

I. INTRODUCTION

Environmental and farm problems have been a long overdue issue to be solved. Wastes from factories, commercial food processors, small sport- fishing operations, village markets, household kitchens and leftovers are some of the contributors to prevalent environmental, health and farming problems. It is observed that these wastes are rampant everywhere and efforts to address this bad scenario seems fruitless; hence, discreet disposing of wastes is a timely call to everyone.

The goal to have a clean and green environment is one of the concerns of a good steward. Looking to our environment today is sad to note situation that in urban areas, there is an urgent need for proper disposal of wastes as well as in rural areas.

In our locality, wastes from freshwater fish such as pijanga, hayuan, and tilapia are commonly discarded, contributing to environmental problems. Utilizing these wastes provides an effective way to prevent or minimize the harm they cause to society, particularly to the environment. Addressing this issue calls for the development of technologies that convert these wastes into valuable products that can benefit the community. Through organic agriculture, these fish

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wastes from wet markets can be transformed into useful fertilizers, helping farmers improve soil fertility, crop yield, and overall farm productivity.

Converting these freshwater fish wastes into powder fertilizer is a discreet way to minimize environmental problems that these wastes will contribute. Hence, aside from being beneficial to the community it also helps increase the production yield of basic farm commodities like eggplant.

Ahuja, et al. (2020) reported that composted fish waste nearly doubled fresh matter yield (≈100% increase) and increased dry matter yield by approximately 50% in lettuce (Lactuca sativa) compared with unfertilized soil. Similarly, Perea, Rivas, and Martínez (2019) found that application of fish waste compost at 66 t/ha increased tomato (Solanum lycopersicum) fruit yield by roughly 20–25% compared with unfertilized or mineral fertilized soil, and also produced residual benefits that improved yield in a subsequent lettuce crop.

This is the compelling reason why the researcher wants to implement a research study to evaluate the effect of varying levels of freshwater fish powder fertilizer in eggplant.

II. CONCEPTUAL FRAMEWORK

The conceptual framework for the study on the Production of Freshwater Fish Powder Fertilizer and Evaluating its Efficacy to Eggplant (Solanum Melongena L.) was based on the interrelationship between the varying levels of FFPF, processing, and impact assessment. Figure 1 integrates the variables that influence the production, evaluation, and application of FFPF to the growth and yield of eggplant (Solanum Melongena L.)

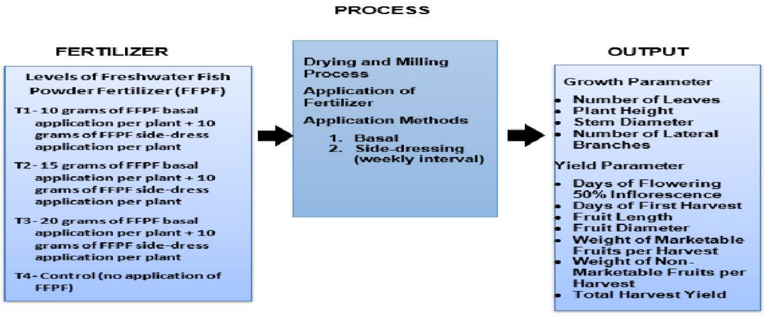

Figure 1. Research Paradigm

III. STATEMENT OF THE PROBLEM

This study was conducted to evaluate the efficacy of the varying levels of freshwater fish powder fertilizer to the growth and yield of eggplant.

Specifically, this study aims to answer the following questions:

1. What is the efficacy of the varying levels of freshwater fish powder fertilizer to the growth and yield of eggplant in terms of number of leaves, plant height, stem diameter, number of lateral branches, days of flowering 50% inflorescence, days of first harvest, fruit length, fruit diameter, weight of marketable fruits per harvest, weight of non-marketable fruits per harvest, and total harvest yield?

2. Which of the treatments will give the best result in the growth and yield of eggplant in terms of number of leaves, plant height, stem diameter, number of lateral branches, days of flowering 50% inflorescence, days of first harvest, fruit length, fruit diameter, weight of marketable fruits per harvest, weight of non-marketable fruits per harvest, and total harvest yield?

3.Is there a significant difference on the efficacy of the varying levels of freshwater fish powder fertilizer to the growth and yield of eggplant in terms of number of leaves, plant height, stem diameter, number of lateral branches, days of flowering 50% inflorescence, days of first harvest, fruit length, fruit diameter, weight of marketable fruits per harvest, weight of non-marketable fruits per harvest, and total harvest yield?

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IV. RESEARCH METHODS

Research Design

This experimental research study was laid-out using Randomized Complete Block Design (RCBD). It consists of four (4) treatments with four (4) replications. Each replicate had ten (10) experimental plants. A total of one hundred sixty (160) experimental plants was used. Fish powder fertilizer is commonly applied at moderate rates because its high nitrogen and micronutrient content supports strong vegetative growth while minimizing the risk of nutrient burn. Recommended application rates generally range from 200–400 kg per hectare for field vegetables or 10–20 grams per plant (Ahuja et al., 2020).

The experimental treatments are the following:

T_1- 10 grams of FFPF basal application per plant + 10 grams of FFPF side-dress application per plant
T_2- 15 grams of FFPF basal application per plant + 10 grams of FFPF side dress application per plant
T3- 20 grams of FFPF basal application per plant + 10 grams of FFPF side-dress application per plant
T_4- Control (no application of FFPF)

Research Environment

This study was conducted at Barangay Paco, Mainit, Surigao Del Norte, for a period of 127 days. The study took place in an agricultural area that can support the healthy growth of Eggplant (Solanum melongena L.) The research was set up using prepared plots in an open field where the plants can receive natural sunlight, good air circulation, and suitable temperature conditions. Before applying the treatments, the experimental site was carefully prepared so that the soil in all plots is as uniform as possible. Soil analysis was conducted to check for similarities in soil texture, nutrient levels, and pH. Throughout the entire experiment, all eggplant plants were treated in the same manner. Watering schedules, weed removal, and pest management were done consistently in all groups to avoid influencing the results.

Subject of the Study

In this experimental study, the subject was eggplant plants. These plants were used to assess how Freshwater Fish Powder Fertilizer (FFPF) function as an organic fertilizer. F1 eggplant seeds will be purchased at Cropland Farm Supply at Magpayang, Mainit Surigao del Norte. Each plot contains 10 hills, with a total of 160 healthy and uniformly grown eggplant seedlings will be selected for the experiment. Experimental hills of eggplant were applied with different levels of freshwater fish powder fertilizer and then the growth and yield of eggplant were determined. Seedlings were randomly assigned to the different treatment groups, which includes the control, 10 grams of FFPF basal application per plant + 10 grams of FFPF side-dress application per plant, 15 grams of FFPF basal application per plant + 10 grams of FFPF side-dress application per plant, and 20 grams of FFPF basal application per plant + 10 grams of FFPF side-dress application per plant. All experimental plots were kept under similar environmental conditions to ensure consistent exposure to sunlight, water, and soil. Throughout the duration of the study, the eggplant plants served as the biological subject from which data on growth, yield, and soil properties were gathered.

Research Instruments

In this study, several plant growth measurement instruments were utilized to assess how the eggplant plants respond to the different treatments. A ruler was used to measure the height of eggplant and the length of its fruits. To obtain precise measurements of the stem and fruit diameter, a digital vernier caliper was used to measure the thickness of the cucumber fruit. In addition, a digital weighing scale was used to measure the weight of the harvested fruits. Furthermore, laboratory analyses were conducted to evaluate the properties of the soil, as well as the nutrient content of the organic fertilizer that was applied in this study.

Data Analysis

Vegetative growth parameters (plant height, number of leaves, stem diameter, and number of lateral branches) measured weekly were analyzed using repeated-measures General Linear Model (GLM). The measurement period was

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treated as the within-subjects factor, while the FFPF treatment was treated as the between-subjects factor. A repeated-measures GLM was used because repeated observations from the same experimental unit are correlated, and the model accounts for within-unit dependency while improving the precision of treatment comparisons (Field, 2018). Mauchly's test of sphericity was used to evaluate the sphericity assumption. When sphericity was violated, the Greenhouse-Geisser correction was applied because violation of sphericity can inflate Type I error rates.

Yield parameters measured across eight harvests, including fruit length, fruit diameter, weight of marketable fruit, and weight of non-marketable fruit, were analyzed using repeated-measures GLM. The harvest period was treated as the within-subjects factor, while the FFPF treatment was treated as the between-subjects factor. Polynomial contrasts were used to determine whether yield responses across harvest periods followed linear or higher-order temporal patterns. Total harvest yield, which represented cumulative productivity across the eight harvests, was analyzed using one-way analysis of variance (ANOVA) to compare treatment means (Montgomery, 2017).

A composite soil sample was analyzed before planting to establish the initial soil chemical condition of the experimental area. The before-planting baseline soil-test values were obtained from the composite soil sample, whereas the after-harvest soil-test values were obtained from each treatment replicate and pooled. Change scores were computed by subtracting the common baseline value from the after-harvest measurement of each treatment replicate, and the resulting change scores were analyzed using one-way ANOVA. All statistical procedures were analyzed using SPSS version 26 for Windows.

V. RESULTS AND DISCUSSIONS

Heavy Metal Content and Nutrient Composition

The freshwater fish powder fertilizer (FFPF) sample contained 6.00% nitrogen (N), 11.00% phosphorus (P_2O_5), 0.168% potassium (K_2O), and less than 1.0 mg/kg lead.

Table 1. Heavy metal content and nutrient composition of freshwater fish powder fertilizer (FFPF)

Nutrient	Freshwater Fish Powder Fertilizer (FFPF)	Test Method
Lead	Less than 1.0**	Flame AAS
Nitrogen	6.00	Kjeldahl Method
Phosphorus	11.00	Colorimetric
Potassium	0.168	Flame AES

FFPF = freshwater fish powder fertilizer; N = nitrogen; P_2O_5 = phosphorus expressed as phosphate; K_2O = potassium expressed as potash; AAS = atomic absorption spectrophotometry; AES = atomic emission spectrophotometry. Values represent laboratory analysis results and were not subjected to statistical analysis.

The 6.00% nitrogen content is consistent with the documented composition of fish tissues. Konosu (1974) analyzed nitrogen constituents in eight fish species and found that free amino acids, creatine, and trimethylamine oxide accounted for 90% of total nitrogen, confirming that fish muscle is nitrogen-rich. This finding aligns with the present result because the protein content of freshwater fish powder accounts for the measured nitrogen level. Nitrogen functions as a structural component of amino acids, proteins, nucleic acids, chlorophyll, enzymes, and hormones, all of which are required for vegetative growth (Dubey et al., 2021). Nitrogen released through microbial mineralization of fish proteins may supply plant-available ammonium and nitrate to support these growth processes.

The 11.00% phosphorus level is consistent with its role in plant metabolism. White and Hammond (2008) emphasized that phosphorus governs phosphate-dependent metabolism and is essential for ATP formation, membrane synthesis, and plant productivity, and that plants have evolved diverse mechanisms to acquire and use phosphorus efficiently, given its limited availability in most soils. The present result indicates that the high P_2O_5 concentration in FFPF may support ATP production and membrane formation, which are required for root proliferation, flowering, and fruit development.

The 0.168% potassium content indicates a nutritional imbalance in the FFPF. Potassium starvation causes dehydration of plant tissues, reduces shoot growth, impairs water-use efficiency, and increases stomatal conductance, thereby compromising plants' ability to regulate stomatal closure under water stress (Arquero et al., 2006). The low potassium content of FFPF may predispose treated crops to impaired stomatal regulation and reduced stress tolerance unless potassium is supplemented. Brod et al. (2023) likewise reported that fish sludge fertilizers showed unbalanced nutrient composition, with low potassium content relative to crop requirements and variable nitrogen quality depending on processing method and origin.

The lead concentration of less than 1.0 mg/kg indicates minimal heavy metal contamination in FFPF. This result is notable because the freshwater fish waste used in the present study was sourced from Lake Mainit, the same body of water from which Laudiño et al. (2023) sourced their freshwater fish waste.

Number of Leaves

The number of leaves was significantly affected by measurement period ($p < 0.001$, partial $\eta^2 = 0.961$) and by the interaction between measurement period and treatment ($p = 0.001$, partial $\eta^2 = 0.702$). All polynomial contrasts for the measurement period were significant ($p < .001$), with the linear component having the largest effect (partial $\eta^2 = 0.968$). For the interaction, the linear ($p = 0.001$), cubic ($p = 0.005$), and fourth-order ($p = .014$) contrasts were significant. The treatment effect was significant ($p < .001$, partial $\eta^2 = 0.809$), with T3 recording the highest mean, followed by T2, T1, and T4. T2 and T3 were significantly higher than T4 ($p < 0.05$), and T3 differed significantly from T1 ($p = 0.018$), while the remaining comparisons were not significant.

Table 2. Effect of freshwater fish powder fertilizer on number of leaves of eggplant across measurement periods

Treatment	Week 1	Week 2	Week 3	Week 4	Week 5	Overall Mean
Treatment 1	4.68	5.70	7.38	16.95	21.28	11.19^{b}
Treatment 2	5.20	6.70	9.40	20.23	25.25	13.35^{ab}
Treatment 3	5.35	7.05	10.15	23.83	28.60	14.99^{a}
Treatment 4	4.30	5.20	6.10	11.38	13.45	8.08^{c}
Within-measurement	p-Value	η^2	Linear	Quadratic	Cubic	Order 4
Mauchly's Test of Sphericity	<0.001***	0.295				
Measurement periods	<0.001***	0.96	<0.001***	<0.001***	<0.001***	<0.001***
Measurement periods * Treatment	0.001**	0.70	0.001**	0.11ns	0.005**	0.014*
Between-treatment	p-Value	η^2				
Treatment	0.001**	0.724				

Means in the overall mean column followed by the same letter are not significantly different based on Tukey HSD at the 5% level. η^2 = partial eta squared; ns = not significant; * = significant at $p \leq 0.05$; ** = significant at $p \leq 0.01$; *** = significant at $p \leq 0.001$. Greenhouse-Geisser correction was applied when the sphericity assumption was violated

The significant increase in leaf number under freshwater fish powder fertilizer (FFPF) may be attributed to the roles of nitrogen and phosphorus in regulating the shoot apical meristem, leaf primordium initiation, and leaf expansion. Dubey et al. (2021) established that nitrogen is a structural component of amino acids, proteins, nucleic acids, chlorophyll, enzymes, and hormones, all of which are required for the production and development of new leaves and photosynthetically active tissues. The findings align with the present results, as the nitrogen supplied by FFPF may have met these biochemical requirements, thereby explaining the greater leaf production in fertilized plants compared with the unfertilized control. Lü et al. (2007) demonstrated that the protein fraction of fish residues is biodegradable, confirming that fish-derived materials can serve as a nitrogen source following microbial decomposition. The findings

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agree with the present results, as the progressive release of ammonium and nitrate from fish proteins may have maintained nitrogen availability throughout the five weeks, consistent with the increase in leaf number across measurement weeks.

The effect on leaf number is also consistent with hormonal control of leaf initiation through nitrogen-responsive cytokinin metabolism. Sakakibara (2020) showed that nitrogen stimulates cytokinin biosynthesis and root-to-shoot transport of trans-zeatin-type cytokinins, thereby maintaining the shoot apical meristem and regulating organ initiation in response to nitrogen supply. The findings agree with the present results, as nitrogen gradually released from FFPF may have enhanced cytokinin levels in the meristem, promoted leaf primordium initiation, and increased leaf counts in fertilized treatments. The highest mean leaf number in T3 suggests that the highest application rate provided sustained nitrogen availability for cytokinin-driven leaf initiation.

Phosphorus supports the metabolic processes required for leaf formation and expansion. In phosphorus-deprived soybeans, Chiera et al. (2005) found that leaf initiation and leaf expansion were inhibited even when ATP concentrations in shoot meristems remained at control levels, concluding that a signaling mechanism independent of energy supply suppresses cell division in shoot growth regions under phosphorus stress. The phosphorus supplied by FFPF in the present study may have affected leaf production by meeting metabolic energy demands and preventing phosphorus-deficiency signaling that would otherwise restrict meristematic activity.

The significant measurement period × treatment interaction, with linear, cubic, and fourth-order polynomial components, indicates that the leaf production response to FFPF was not uniform across weeks. Amzallag (2002) showed that plant growth responses to nutrient availability depend on timing, with adaptive responses occurring during critical periods. Early-treated plants stabilized growth rate relative to controls, whereas late-treated plants showed greater effects of nutrient limitation. The FFPF-treated eggplants in the present study likely experienced stronger leaf flushes at certain developmental stages rather than a strictly linear increase across weekly measurements, as microbial mineralization rates and plant demand shifted across the five-week period, which aligned with the growth responses observed by Amzallag (2002).

The Tukey HSD results indicate that T2 and T3 outperformed T4, and that T3 also exceeded T1, suggesting that the lowest FFPF rate was less effective than the highest in sustaining leaf production. At the same time, the nonsignificant difference between T2 and T3 indicates that returns diminish once the plants reach nutrient sufficiency. Kuchay and Zargar (2016) reported that relative growth rate and net assimilation rate in brinjal are highest during the vegetative phase, with strong allocation toward leaves before the transition to reproductive development. The findings of Kuchay and Zargar (2016) align with the present results, as the measurement period effect from week 1 to week 5 reflects the vegetative growth pattern in eggplant, while the significant treatment effect from T1 to T4 confirms that FFPF improved the nutritional capacity of eggplant plants during the vegetative stage.

Plant Height

Plant height was significantly affected by measurement period ($p < 0.001$, partial $\eta^2 = 0.989$) and by the interaction between measurement period and treatment ($p < 0.001$, partial $\eta^2 = 0.685$). All polynomial contrasts for the measurement period were significant ($p < .001$), with the linear component showing the largest effect (partial $\eta^2 = 0.992$). For the interaction, only the linear contrast was significant ($p = 0.001$, partial $\eta^2 = 0.737$). Treatment had a significant effect ($p = 0.001$, partial $\eta^2 = 0.724$), with T3 recording the highest mean, followed by T2, T1, and T4. T1, T2, and T3 were each significantly higher than T4 ($p < 0.05$), with no significant differences among the fertilized treatments.

Table 3. Effect of freshwater fish powder fertilizer on plant height of eggplant across measurement periods

Treatment	Week 1	Week 2	Week 3	Week 4	Week 5	Overall Mean
Treatment 1	8.45	10.03	18.33	35.10	44.33	23.25^a
Treatment 2	8.53	11.15	19.98	38.95	48.83	25.46^a
Treatment 3	10.40	12.68	21.00	41.63	51.23	27.39^a

Treatment 4	5.38	7.08	12.53	26.73	32.15	16.77^{b}
Within-measurement	p-Value	η^2	Linear	Quadratic	Cubic	Order 4
Mauchly's Test of Sphericity	<0.001***	0.427				
Measurement periods	<0.001***	0.99	<0.001***	<0.001***	<0.001***	<0.001***
Measurement periods * Treatment	<0.001***	0.69	<0.001***	0.08^{ns}	0.32^{ns}	0.25^{ns}
Between-treatment	p-Value	η^2				
Treatment	0.001**	0.724				

Means in the overall mean column followed by the same letter are not significantly different based on Tukey HSD at the 5% level. η^2 = partial eta squared; ns = not significant; * = significant at $p \leqslant 0.05$; ** = significant at $p \leqslant 0.01$; *** = significant at $p \leqslant 0.001$. Greenhouse-Geisser correction was applied when the sphericity assumption was violated

The significant increase in eggplant height under freshwater fish powder fertilizer (FFPF) may be attributed to nitrogen and phosphorus effects on meristematic growth, tissue expansion, and nutrient signaling. Dubey et al. (2021) established that nitrogen is a structural component of amino acids, proteins, nucleic acids, chlorophyll, enzymes, and hormones, and that adequate nitrogen supports cell division, chloroplast development, and vegetative growth. The findings of Dubey et al. (2021) align with the present results, as the nitrogen supplied by FFPF may have supported these growth processes, explaining the greater shoot elongation in fertilized plants than in the unfertilized control. Lü et al. (2007) demonstrated through kinetic modeling that the protein fraction of fish residues is biodegradable under anaerobic decomposition, confirming that fish-derived proteins can serve as a source of mineralizable nitrogen. The findings of Lü et al. (2007) support the interpretation that microbial hydrolysis of fish proteins in soil may have gradually released ammonium and nitrate, thereby sustaining nitrogen availability throughout the five-week measurement period of the present study. Beyond its nutritional role, nitrogen regulates growth through cytokinin-mediated meristem activity. Sakakibara (2020) showed that nitrogen stimulates cytokinin biosynthesis and root-to-shoot cytokinin transport, particularly trans-zeatin-type cytokinins, which maintain the shoot apical meristem and regulate shoot growth in response to nitrogen supply. The findings of Sakakibara (2020) align with the present results, as greater nitrogen availability from FFPF may have enhanced cytokinin-mediated meristem activity, promoted internode elongation, and sustained the height advantage observed from week 1 to week 5.

Phosphorus contributes to plant growth through nucleic acid synthesis, phosphorylation reactions, and ATP metabolism. In phosphorus-deprived soybeans, Chiera et al. (2005) found that leaf initiation and shoot expansion were inhibited even when ATP concentrations in shoot meristems were temporarily maintained at control levels, concluding that an energy-independent signaling mechanism suppresses cell division in shoot growth regions under phosphorus stress. The present results suggest that phosphorus supplied by FFPF supported eggplant height not only by meeting metabolic energy demands but also by preventing phosphorus-deficiency signaling that would otherwise restrict meristematic activity. Cerutti and Delatorre (2013) demonstrated in Arabidopsis that nitrogen and phosphorus interact through shared signaling components, with high nitrogen inducing cell division and modifying phosphate transporters through pathways partially mediated by cytokinin. The findings of Cerutti and Delatorre (2013) agree with the present results, indicating that taller plants in T1, T2, and T3 reflect nitrogen and phosphorus stimulation rather than the independent effect of either nutrient.

The measurement period × treatment interaction showed a linear divergence pattern, indicating that the height advantage from FFPF was sustained and consistent with the gradual biodegradation of fish proteins documented by Lü et al. (2007). Kuchay and Zargar (2016) reported that relative growth rate and net assimilation rate in brinjal are highest during the vegetative phase, with strong allocation toward leaves before the transition to reproductive development. The findings of Kuchay and Zargar (2016) align with the present results, as the study period captured the vegetative stage when shoot elongation is most responsive to nutrient availability, explaining the strong main effect of measurement period and the progressive fertilizer-driven divergence in height. Since T1, T2, and T3 did not differ significantly from one another and all exceeded the control, even the lowest FFPF rate was sufficient to alleviate nutrient limitation on plant height, suggesting that the height response plateaued once nutrient sufficiency was achieved.

Stem Diameter

Stem diameter was significantly affected by measurement period ($p < 0.001$, partial $\eta^2 = 0.979$) and by the interaction between measurement period and treatment ($p = 0.012$, partial $\eta^2 = 0.435$). For the measurement period, the linear ($p < 0.001$) and fourth-order ($p < 0.001$) contrasts were significant. For the interaction, the linear ($p = 0.018$) and cubic ($p = 0.034$) contrasts were significant. The treatment effect was significant ($p < 0.001$, partial $\eta^2 = 0.802$), with T3 recording the highest mean, followed by T2, T1, and T4. T2 and T3 were significantly higher than T4, and T3 differed significantly from T1 ($p = 0.027$), while the remaining comparisons were not significant.

Table 4. Effect of freshwater fish powder fertilizer on stem diameter of eggplant across measurement periods

Treatment	Week 1	Week 2	Week 3	Week 4	Week 5	Overall Mean
Treatment 1	0.13	0.23	0.27	0.35	0.39	0.27b
Treatment 2	0.20	0.25	0.29	0.38	0.41	0.31ab
Treatment 3	0.21	0.27	0.31	0.39	0.43	0.32a
Treatment 4	0.12	0.20	0.22	0.28	0.33	0.23c
Within-measurement	p-Value	η^2	Linear	Quadratic	Cubic	Order 4
Mauchly's Test of Sphericity	0.013*	0.637				
Measurement periods	<0.001***	0.98	<0.001***	<0.001***	<0.001***	<0.001***
Measurement periods * Treatment	0.003**	0.44	0.001**	0.22ns	0.59ns	<0.001***
Between-treatment	p-Value	η^2				
Treatment	0.001**	0.802				

Means in the overall mean column followed by the same letter are not significantly different based on Tukey HSD at the 5% level. η^2 = partial eta squared; ns = not significant; * = significant at $p \leqslant 0.05$; ** = significant at $p \leqslant 0.01$; *** = significant at $p \leqslant 0.001$. Greenhouse-Geisser correction was applied when the sphericity assumption was violated

The significant increase in eggplant stem diameter under freshwater fish powder fertilizer (FFPF) may be attributed to nitrogen and phosphorus effects on cambial activity, biomass formation, and assimilate supply to stem tissues. Dubey et al. (2021) established that nitrogen is a component of proteins, amino acids, nucleic acids, chlorophyll, and enzymes, and that adequate nitrogen is indispensable for vegetative development and the growth of both source and sink tissues. Similarly, nitrogen supplied by FFPF in the present study may have supported the protein synthesis, nucleic acid production, and enzymatic activity required for secondary growth and stem biomass accumulation. Lü et al. (2007) demonstrated that the protein fraction of fish residues is biodegradable, confirming that fish-derived materials release nitrogen gradually through microbial decomposition. The findings of Lü et al. (2007) agree with the present results, as the significant linear measurement period × treatment interaction indicates a sustained stem-thickening advantage in fertilized plants rather than a short-term response.

Nitrogen-responsive hormonal regulation further explains the stem-diameter response. Sakakibara (2020) showed that nitrogen availability stimulates cytokinin biosynthesis and root-to-shoot transport of trans-zeatin-type cytokinins, which regulate meristematic activity and shoot growth in response to nitrogen supply. The findings of Sakakibara (2020) align with the present results, as greater nitrogen availability from FFPF may have enhanced meristematic activity in both shoot apices and lateral meristems, thereby supporting stem development. Matsumoto-Kitano et al. (2008) demonstrated that cytokinin is indispensable for cambial development, with cytokinin-deficient mutants showing reduced stem and root thickening. The findings agree with the present results, as the greater stem diameter observed in T2 and T3 may be linked to the nitrogen-cytokinin pathway's effect on cambial proliferation and tissue deposition.

Phosphorus supports ATP production and photosynthetic phosphorylation. Chiera et al. (2005) found that cell division in shoot growth regions was suppressed in phosphorus-deprived soybean through a mechanism independent of ATP availability, concluding that phosphorus deficiency restricts growth through developmental signaling rather than energy limitation. The findings agree with the present results, as phosphorus supplied by FFPF may have promoted stem growth by supporting metabolic demands and preventing phosphorus deficiency, which would otherwise restrict cambial activity. Cerutti and Delatorre (2013) demonstrated in Arabidopsis that nitrogen and phosphorus interact through shared signaling components, with their responses integrated through cytokinin-mediated pathways that coordinate cell division and growth. This finding agrees with the present results on the stem-diameter response in T2 and T3, which reflects combined nitrogen and phosphorus stimulation rather than the independent contribution of either nutrient.

The significant cubic interaction across measurement periods may reflect transient shifts in assimilate allocation as nutrient release from fish powder and plant demand changed over time. In girdling and water-stress experiments in walnut, Daudet et al. (2005) noted that stem diameter variation reflects not only irreversible radial growth but also reversible components, including living-cell dehydration and rehydration, thermal expansion, and internal tissue tensions. The findings of Daudet et al. (2005) partly agree with the present results by supporting stem thickening over time. However, they also imply that oscillations in repeated stem diameter measurements may be influenced by water dynamics rather than by cambial production alone. Cocozza et al. (2018) likewise demonstrated that stem radius variations are synchronous with weather conditions and tissue water relations, with environmental fluctuations producing measurable dendrometer signals independent of true radial growth. The findings of Cocozza et al. (2018) also partly agree with the present results for the same reason, indicating that the cubic interaction may reflect a combination of cambial response and short-term hydration. The Tukey HSD pattern indicates that T2 and T3 exceeded T4, while T3 also exceeded T1, suggesting that higher FFPF rates were required to sustain measurable cambial activity. At the same time, the nonsignificant difference between T2 and T3 indicates that returns decline once the plants reach nutrient sufficiency.

Number of Lateral Branches

The number of lateral branches was significantly affected by measurement period ($p < 0.001$, partial $\eta^2 = 0.942$) and by the interaction between measurement period and treatment ($p = 0.010$, partial $\eta^2 = 0.574$). For the measurement period, the linear ($p < 0.001$) and quadratic ($p = 0.006$) contrasts were significant. For the interaction, the linear ($p = 0.011$) and cubic ($p = 0.016$) contrasts were significant. The treatment effect was significant ($p = 0.001$, partial $\eta^2 = .712$), with T3 recording the highest mean, followed by T2, T1, and T4. T1, T2, and T3 were significantly higher than T4 ($p < 0.05$), with no significant differences among the fertilized treatments.

Table 5. Effect of freshwater fish powder fertilizer on number of lateral branches of eggplant across measurement periods

Treatment	Week 1	Week 2	Week 3	Week 4	Overall Mean
Treatment 1	1.58	2.78	4.48	5.65	3.62a
Treatment 2	1.98	3.70	5.10	6.40	4.29a
Treatment 3	2.33	3.98	5.58	6.70	4.64a
Treatment 4	0.33	1.33	1.93	2.25	1.46b
Within-measurement	p-Value	η^2	Linear	Quadratic	Cubic
Mauchly's Test of Sphericity	<0.001***	0.374			
Measurement periods	<0.001***	0.94	<0.001***	0.006	0.050
Measurement periods * Treatment	<0.001***	0.57	0.011*	0.330	0.016
Between-treatment	p-Value	η^2			
Treatment	0.001**	0.802			

Means in the overall mean column followed by the same letter are not significantly different based on Tukey HSD at the 5% level. η^2 = partial eta squared; ns = not significant; * = significant at $p \leqslant 0.05$; ** = significant at $p \leqslant 0.01$; *** = significant at $p \leqslant 0.001$. Greenhouse-Geisser correction was applied when the sphericity assumption was violated

The significant increase in lateral branch number under freshwater fish powder fertilizer (FFPF) may be attributed to the interaction between nutrient availability and hormonal control of axillary bud outgrowth. Shimizu-Sato et al. (2009) explained that apical dominance is maintained by auxin derived from the intact shoot apex, which suppresses axillary bud outgrowth, while cytokinin acts antagonistically by stimulating bud activation and branching, with the molecular interactions between auxin and cytokinin governing the extent of shoot branching. The greater lateral branch number in FFPF-treated plants suggests that improved nutrient availability shifted the hormonal balance toward axillary bud release, thereby reducing the suppressive effect of apical dominance, supporting the findings by Shimizu-Sato et al. (2009). Sakakibara (2020) demonstrated that nitrogen stimulates cytokinin biosynthesis and root-to-shoot transport of trans-zeatin-type cytokinins, linking nitrogen to hormonal regulation of shoot growth and meristem activity. This finding agrees with the present results, which indicate that nitrogen released from FFPF may have enhanced cytokinin production and axillary bud outgrowth, explaining why all fertilized treatments produced significantly more lateral branches than the unfertilized control. Lü et al. (2007) confirmed that the protein fraction of fish residues is biodegradable, supporting the interpretation that fish-derived materials release nitrogen gradually through microbial decomposition. This sustained nitrogen mineralization may have supported cytokinin biosynthesis across successive measurement periods and contributed to the progressive increase in lateral branch number observed in the present study.

The significant measurement-period effect showed a linear increase, with an additional quadratic component. The absence of lateral branches in week 1 reflected regulation of bud outgrowth, consistent with the principle that branching emerges only after plants reach a critical vegetative stage. Amzallag (2002) showed in Sorghum bicolor that plant growth responses to nutrient availability are conditioned by developmental timing, with adaptive responses expressed only during critical periods of development, and that early-treated plants stabilized growth rate relative to controls, whereas late-treated plants did not.

The cubic interaction between measurement period and treatment indicates that the branching response to FFPF was not uniform throughout the observation period. This pattern likely reflects pulses of bud initiation, shaped by shifts in microbial mineralization and changes in the source-sink balance as plant demand evolved across the study period. The cubic interaction is consistent with the interpretation that organic fertilizer responses are dynamic rather than constant, as nitrogen release from fish proteins may fluctuate with soil microbial activity and environmental conditions.

The between-subjects results show that T1, T2, and T3 all exceeded T4 but did not differ significantly from one another, indicating a threshold response rather than a linear dose response. Once cytokinin production reached a threshold level, it released axillary buds from dormancy, and additional fertilizer did not proportionally increase branch number. Cerutti and Delatorre (2013) demonstrated in Arabidopsis that nitrogen and phosphorus interact through shared signaling components, with nitrogen inducing cell division and phosphorus modifying growth responses through cytokinin-mediated pathways. The findings of Cerutti and Delatorre (2013) could explain why the branching response of eggplant in the present study likely depended on nitrogen and phosphorus nutrition rather than nitrogen alone, with phosphorus from FFPF supporting ATP production and nucleic acid metabolism required for cell division in developing buds. The threshold pattern further indicates that once nutrients reached sufficiency, they fulfilled the hormonal requirement for axillary bud activation.

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Days to 50% Inflorescence and Days to First Harvest

There was no significant treatment effect on days to 50% inflorescence (p = 0.103) or days to first harvest (p = 0.066), and all pairwise comparisons were not significant.

Table 6. Effect of freshwater fish powder fertilizer on reproductive timing of eggplant

Source of variations	Pillai's Trace		p-value	ηp^2
MULTIVARIATE		0.513	0.263	0.257
UNIVARIATE	Days to first bud		Days of first flower fully open	
Treatment 1	41.00 ± 3.46		77.83 ± 2.65	
Treatment 2	39.75 ± 5.68		75.43 ± 4.54	
Treatment 3	38.00 ± 4.89		73.53 ± 5.18	
Treatment 4	46.00 ± 2.31		81.30 ± 1.78	
Significance	p – value	ηp^2	p – value	ηp^2
	0.103^{ns}	0.391	0.066^{ns}	0.438

Values are presented as mean ± standard deviation. Reproductive timing parameters were analyzed using multivariate GLM. ηp^2 = partial eta squared; ns = not significant at the 5% level. Pillai's Trace was used to evaluate the multivariate treatment effect.

The nonsignificant effect of freshwater fish powder fertilizer (FFPF) on days to 50% inflorescence and first harvest suggests that developmental and environmental factors influenced eggplant reproductive timing more than fertilizer treatment did. Kong et al. (2010) identified 10 FLOWERING LOCUS T (FT) homologs in soybean. They demonstrated that GmFT2a and GmFT5a function as flowering integrators, are upregulated under short-day conditions, are downregulated under long-day conditions, and are regulated by the PHYA-mediated photoperiodic system. Although Kong et al. (2010) focused on soybean rather than eggplant, the findings support the interpretation that photoperiodic signaling pathways strongly govern flowering time and that differences in fertilizer input may not override floral regulatory mechanisms. Subramaniam and Kumar (2023) identified 12 FT/TFL1 gene homologs in eggplant across four cultivars. They confirmed that eggplant possesses the same core flowering regulatory framework, with diversification among FT-like genes suggesting adaptation to environmental stimuli. The findings of Subramaniam and Kumar (2023) support the present study's interpretation that days to 50% inflorescence were determined more by genotype and environmental conditions than by FFPF application.

The nonsignificant fertilizer effect is further supported by eggplant-specific evidence linking flowering to plant development and thermal accumulation. Ishida (1972) showed that, in early-harvest eggplant varieties, the node position of the first flower was influenced by cotyledon removal timing and day length, demonstrating that first-flower formation is associated with plant development and the photoperiodic environment during early growth. The findings of Ishida (1972) agree with the present results, as developmental programming and light sensitivity in eggplant may make large shifts in reproductive timing unlikely in response to organic fertilizer rate. León Pacheco et al. (2019) demonstrated, across 15 eggplant genotypes grown under open-field conditions, that growing degree days predicted phenological transitions, including vegetative growth, first flowering, and fructification, and that genotypes requiring fewer growing degree days for fruit production achieved higher productivity. The strong dependence of reproductive timing on accumulated thermal time and genotype explains why FFPF treatments did not produce a statistically significant difference in days to 50% inflorescence or days to first harvest, despite improving vegetative growth.

Fruit Length per Harvest

Fruit length was significantly affected by harvest period (p = 0.038, partial $\eta^2 = 0.230$), whereas the interaction between harvest period and treatment was not significant (p = 0.824, partial $\eta^2 = 0.109$). Polynomial contrasts showed significant linear (p = 0.013) and sixth-order (p = 0.009) components, while the remaining trend components were not significant. Treatment had a significant effect on fruit length (p = 0.002, partial $\eta^2 = 0.696$), with the highest mean recorded in the 20 g basal + 10 g side-dress treatment (21.25 cm), followed by the 15 g basal + 10 g side-dress treatment (19.28 cm), the 10 g basal + 10 g side-dress treatment (18.997 cm), and the no-fertilizer treatment (14.49 cm). Tukey HSD pairwise comparisons showed that all fertilizer treatments differed significantly from the no-fertilizer treatment, whereas the fertilizer treatments did not differ significantly from one another.

Table 7. Effect of freshwater fish powder fertilizer on fruit length of eggplant across harvest periods

Treatment	H 1	H 2	H 3	H 4	H 5	H 6	H 7	H 8	Overall Mean
Treatment 1	15.06	15.83	21.99	19.98	18.79	19.85	20.17	20.31	18.10^{a}
Treatment 2	11.72	18.55	21.81	20.75	19.48	19.94	20.24	21.77	19.28^{a}
Treatment 3	17.63	21.27	23.44	22.42	20.33	20.93	21.05	22.92	21.25^{a}
Treatment 4	9.63	8.75	18.13	10.08	16.42	17.18	18.75	16.99	14.49^{b}
Within-measurement	p-Value	η^2	Linear	Quadratic	Cubic	Order 4	Order 5	Order 6	Order 7
Mauchly's Test	<0.001***	0.314							
Harvest periods	0.038*	0.23	0.013*	0.16^{ns}	0.08^{ns}	0.59^{ns}	0.27^{ns}	0.009**	0.24^{ns}
Harvest periods * Treatment	0.82^{ns}	0.11	0.63^{ns}	0.95^{ns}	0.52^{ns}	0.98^{ns}	0.91^{ns}	0.25^{ns}	0.25^{ns}
Between-treatment	p-Value	η^2							
Treatment	0.002**	0.696							

Means in the overall mean column followed by the same letter are not significantly different based on Tukey HSD at the 5% level. η^2 = partial eta squared; ns = not significant; * = significant at $p \leqslant 0.05$; ** = significant at $p \leqslant 0.01$; *** = significant at $p \leqslant 0.001$. Greenhouse-Geisser correction was applied when the sphericity assumption was violated.

The significant effect of freshwater fish powder fertilizer (FFPF) on overall mean fruit length, without a significant harvest period × treatment interaction, indicates that FFPF improved fruit elongation across harvests without altering the temporal pattern of fruit-length change. Obroucheva (2014) explained that fruit growth in fleshy fruits depends on auxin synthesized in the developing seed and gibberellins produced in the pericarp, which drive pericarp cell division and elongation following pollination and fertilization. This hormonal regulation of cell proliferation and expansion may explain how improved nutrient availability from FFPF supported the metabolic requirements of auxin- and gibberellin-mediated growth processes. Dubey et al. (2021) established that nitrogen is indispensable for amino acid, protein, enzyme, and nucleic acid synthesis, all of which are required for growth in dividing and expanding tissues. This finding aligns with the present results, as nitrogen supplied by FFPF may have sustained the biosynthetic capacity of developing pericarp tissues, supporting the cell division and elongation processes that determine final fruit length. Carstensen et al. (2018) demonstrated in barley that phosphorus deficiency inhibits ATP synthase activity, disrupts photosynthetic electron transport, and reduces CO_2 fixation, thereby restricting assimilate supply available for growth. These findings support the interpretation that phosphorus provision in FFPF may have sustained ATP and carbon metabolism in expanding reproductive tissues, contributing to the improved fruit elongation observed across all fertilized treatments.

The finding that all three fertilizer treatments, regardless of application rate, produced significantly longer fruits than the no-fertilizer control but did not differ significantly from one another suggests that even the lowest FFPF rate (10 g basal + 10 g side-dress) was sufficient to meet the nutrient threshold required for improved fruit elongation. Increasing the dose beyond this level produced no significant additional gain. Ho (1996) concluded that, in tomato, yield is limited by sink strength rather than by source supply, and that both cell number and cell size determine fruit size, with the rate of fruit expansion affected by assimilate supply, temperature, and water relations. This finding indicates that once sufficient nutrient supply is established to meet the demands of reproductive sinks, additional nutrient input does not yield proportional increases in fruit length. This lack of proportional response explains the plateau in fruit-length response observed among the fertilizer treatments in the present study. The large treatment effect size (partial $\eta^2 = 0.696$) indicates that treatments, particularly whether fertilizer was applied, were the dominant source of between-subject variation in fruit length, reinforcing the practical importance of FFPF application regardless of dose.

The significant linear trend ($p = 0.013$) indicates an overall upward trend in fruit length across successive harvests, consistent with gradual improvement in plant resource status as the crop matured. The additional sixth-order polynomial component ($p = 0.009$) indicates that the overall trend was not monotonic and was accompanied by an oscillatory pattern across the eight harvest periods, suggesting recurring cycles of resource availability and depletion. Zhang et al. (2005) showed in pear that assimilate availability during the cell division period was crucial for fruit growth and correlated with fruit size, and that differences in final fruit size were attributable to differences in mesocarp cell number established during the early growth phase. These findings suggest that the within-harvest oscillations in fruit length across successive cohorts reflected periodic fluctuations in assimilate availability during the cell division phase, with transient competition among simultaneously developing fruits reducing mesocarp cell number and final length of later-initiated fruits within some harvest windows. The nonsignificant harvest period × treatment interaction indicates that FFPF increased average resource availability in eggplant plants across harvest periods without altering the source-sink dynamics that governed temporal variation in fruit size.

Fruit Diameter per Harvest

Fruit diameter was significantly affected by treatment ($p = 0.012$, partial $\eta^2 = 0.590$). The main effect of harvest period was also significant after Greenhouse-Geisser correction for violation of sphericity ($p = 0.014$, partial $\eta^2 = 0.270$). The interaction between harvest period and treatment was not significant ($p = 0.730$). For the polynomial contrasts of harvest period, the linear ($p = 0.007$), quadratic ($p = 0.021$), and seventh-order ($p = 0.013$) components were significant, while the remaining contrasts were not significant. For the interaction, only the seventh-order contrast was significant ($p = 0.004$). Across treatments, T3 recorded the highest mean fruit diameter, followed by T2, T1, and T4. Pairwise comparisons showed that only T3 was significantly higher than T4 ($p = 0.011$), while the remaining treatment comparisons were not significant.

Table 8. Effect of freshwater fish powder fertilizer on fruit diameter of eggplant across harvest periods

Treatment	H 1	H 2	H 3	H 4	H 5	H 6	H 7	H 8	Overall Mean
Treatment 1	1.04	1.03	1.48	1.54	1.52	1.43	1.38	1.42	1.36^{ab}
Treatment 2	0.78	1.43	1.48	1.59	1.55	1.51	1.38	1.44	1.40^{ab}
Treatment 3	1.20	1.47	1.71	1.61	1.57	1.52	1.50	1.56	1.52^{a}
Treatment 4	0.58	0.70	1.27	0.73	1.47	1.28	1.30	1.29	1.07^{b}
Within-measurement	p-Value	η²	Linear	Quadratic	Cubic	Order 4	Order 5	Order 6	Order 7
Mauchly's Test	<0.001***	0.354							

Harvest periods	0.014*	0.27	0.007**	0.021*	0.17^{ns}	0.87^{ns}	0.99^{ns}	0.33^{ns}	0.013*
Harvest periods * Treatment	0.70^{ns}	0.14	0.48^{ns}	0.91^{ns}	0.69^{ns}	0.80^{ns}	0.76^{ns}	0.71^{ns}	0.004**
Between-treatment	p-Value	η²							
Treatment	0.012*	0.59							

Means in the overall mean column followed by the same letter are not significantly different based on Tukey HSD at the 5% level. η^2 = partial eta squared; ns = not significant; * = significant at $p \leqslant 0.05$; ** = significant at $p \leqslant 0.01$; *** = significant at $p \leqslant 0.001$. Greenhouse-Geisser correction was applied when the sphericity assumption was violated.

The significant treatment effect on fruit diameter, with partial $\eta^2 = 0.590$, indicates that FFPF improved radial fruit growth, although the effect was most evident at the highest application rate. The fact that only T3 differed significantly from the no-fertilizer control, while T1 and T2 did not, suggests that a higher nutrient-input threshold was required to produce a detectable gain in fruit diameter compared with the threshold required for some vegetative traits. The low potassium content of FFPF (0.168% K_2O) may have contributed to this dose-dependent response. Arquero et al. (2006) demonstrated in olive cuttings that potassium starvation caused dehydration of plant parts, reduced shoot growth, impaired water-use efficiency, and compromised the ability to regulate water balance, processes that are directly relevant to turgor-driven cell enlargement in fruit tissues. These findings suggest that the limited potassium supply from lower FFPF doses may have constrained pericarp cell expansion through reduced turgor pressure, raising the nutrient threshold at which diameter gains became statistically detectable. Dubey et al. (2021) established that nitrogen is indispensable for amino acid, protein, enzyme, and nucleic acid synthesis required for sink tissue growth. This supports the present finding that T3, which supplied the greatest nutrient input, produced the largest fruit diameter because it may have better supported the combined demands of biosynthesis and turgor-driven expansion than the lower FFPF rates. Carstensen et al. (2018) showed that phosphorus deficiency inhibits ATP synthase activity, disrupts photosynthetic electron transport, and reduces CO_2 fixation, thereby restricting assimilate production and movement to reproductive organs. This finding supports the present results because phosphorus supplied through FFPF may have sustained carbon metabolism required for assimilate deposition in expanding fruit tissues, particularly in T3, where total nutrient input was greatest.

The significant linear contrast ($p = 0.007$) reflects a general upward trend in fruit diameter across successive harvests, consistent with improved plant resource status and progressive source-sink establishment over the cropping period. The significant quadratic component ($p = 0.021$) indicates that this upward trend was not uniform but followed a curvilinear trajectory, with diameter increasing during the middle harvests and leveling off or declining toward the final harvests. This pattern is consistent with assimilate supply increasing during peak plant productivity and declining as plant senescence begins. The significant seventh-order contrast ($p = 0.013$) captures a late-harvest oscillation, suggesting short-term fluctuations in assimilate partitioning toward fruit expansion near the end of the cropping cycle. Zhang et al. (2005) showed in pear that assimilate availability during the cell division period was crucial for fruit growth and correlated with final fruit size, with differences in final size attributable to mesocarp cell number established during the early growth phase. These findings align with the harvest-period trends observed in the present study, where early assimilate supply may have set the capacity for radial expansion, while competition among simultaneously developing fruits influenced diameter variation across harvests independently of fertilizer treatment.

Weight of Marketable Fruit per Harvest

Marketable fruit weight was significantly affected by harvest period after Greenhouse-Geisser correction for violation of sphericity ($p = 0.001$, partial $\eta^2 = 0.380$). The main effect of treatment was also significant ($p = 0.001$, partial $\eta^2 = 0.740$), while the interaction between harvest period and treatment was not significant ($p = 0.360$). Polynomial contrasts for harvest period showed significant linear ($p = 0.030$), quadratic ($p = 0.007$), fifth-order ($p = 0.004$), and sixth-order ($p = 0.001$) components, while the cubic, fourth-order, and seventh-order components were not significant. For the interaction, the linear ($p = 0.040$) and seventh-order ($p = 0.031$) contrasts were significant, while the remaining contrasts were not significant. Across treatments, T3 recorded the highest mean marketable fruit weight, followed by T1, T2, and T4. Pairwise comparisons showed that T1, T2, and T3 each produced significantly greater marketable fruit weight than T4 ($p < .05$), while differences among T1, T2, and T3 were not significant.

Table 9. Effect of freshwater fish powder fertilizer on marketable fruit weight of eggplant across harvest periods

Treatment	H 1	H 2	H 3	H 4	H 5	H 6	H 7	H 8	Overall Mean
Treatment 1	78.75	74.38	124.90	120.00	105.88	108.52	95.49	92.77	100.08^{a}
Treatment 2	66.56	55.63	131.98	135.00	106.15	111.18	95.61	96.25	99.79^{a}
Treatment 3	113.54	104.17	152.13	136.14	110.10	114.49	102.65	100.85	116.76^{a}
Treatment 4	16.25	0.00	88.75	55.00	77.50	99.46	86.54	87.50	63.87^{b}
Within-measurement	p-Value	η²	Linear	Quadratic	Cubic	Order 4	Order 5	Order 6	Order 7
Mauchly's Test	<0.001***	0.424							
Harvest periods	<0.001***	0.38	0.03^{ns}	0.007**	0.32^{ns}	0.11^{ns}	0.004*	<0.001***	0.33^{ns}
Harvest periods * Treatment	0.36^{ns}	0.22	0.04*	0.88^{ns}	0.82^{ns}	0.9^{ns}	0.9^{ns}	0.51^{ns}	0.031*
Between-treatment	p-Value	η²							
Treatment	0.001***	0.74							

Means in the overall mean column followed by the same letter are not significantly different based on Tukey HSD at the 5% level. η^2 = partial eta squared; ns = not significant; * = significant at $p \leqslant 0.05$; ** = significant at $p \leqslant 0.01$; *** = significant at $p \leqslant 0.001$. Greenhouse-Geisser correction was applied when the sphericity assumption was violated

The significant treatment effect (partial $\eta^2 = 0.740$) indicates that FFPF application, at all tested rates, increased marketable fruit weight relative to the unfertilized control without altering the overall harvest-to-harvest pattern. The finding that all three fertilizer treatments, regardless of application rate, differed significantly from the no-fertilizer control but not from one another indicates that the minimum FFPF dose tested (10 g basal + 10 g side-dress) was sufficient to meet the nutrient threshold required for improved marketable fruit production. Increasing the dose beyond this level did not produce a statistically distinguishable additional gain in marketable fruit weight. Dubey et al. (2021) established that nitrogen is indispensable for amino acid synthesis, chlorophyll formation, enzymatic activity, and vegetative growth, underpinning the photosynthetic source capacity required to supply assimilates to developing reproductive sinks. This finding agrees with the present results because nitrogen supplied by FFPF at all application rates may have supported leaf photosynthetic capacity and the biosynthetic activity of source tissues, improving assimilate supply for fruit development and retention across successive harvests. Carstensen et al. (2018) demonstrated that phosphorus deficiency inhibits ATP synthase activity, disrupts photosynthetic electron transport, and reduces CO_2 fixation, thereby restricting carbon supply for growth and reproduction. The phosphorus provision of FFPF may

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therefore have maintained carbon assimilation in fertilized plants, supporting assimilate production required for higher marketable fruit weight across harvests.

The treatments ranked in the following order: T3, T1, T2, and T4. This pattern warrants attention because T1 (10 g basal + 10 g side-dress) numerically exceeded T2 (15 g basal + 10 g side-dress), departing from the dose-ordered ranking observed for several morphological traits. Although this difference was not statistically significant, the ranking suggests that the relationship between FFPF dose and marketable fruit weight was not strictly monotonic within the fertilized range. This pattern may reflect differences in nutrient-release timing, fruit set, fruit retention, or assimilate partitioning among treatments. Nardozza et al. (2020) demonstrated that following cell division, fruit expansion depends on osmotic adjustment, water uptake, and carbohydrate accumulation, and that carbon starvation reduced cytokinin levels and restricted fruit cell expansion. The findings of Nardozza et al. (2020) support the present results because improved vegetative development under fertilized treatments may have enhanced photosynthate production and transport capacity, allowing fertilized plants to sustain greater marketable fruit weight across harvests.

The significant linear contrast ($p = 0.030$) indicates a general upward trend in marketable fruit weight across the cropping period, consistent with progressive establishment of reproductive capacity and canopy development over successive harvests. The significant quadratic component ($p = 0.007$) suggests that this upward trend was curvilinear, with marketable fruit weight increasing during the middle harvests and plateauing or declining toward the final harvests as source capacity declined with plant aging. The significant fifth-order ($p = 0.004$) and sixth-order ($p = 0.001$) contrasts reflect additional oscillations superimposed on the main trend, likely capturing recurring cycles of fruit production and resource depletion caused by competition among developing fruit cohorts for assimilates. Bertin (1995) demonstrated in tomato that fruit set and development are influenced by competition among developing reproductive organs for assimilates, with distal fruits subject to double competition within and among inflorescences. These findings explain the multi-order polynomial structure of the harvest-period effect observed in the present study, where alternating peaks and troughs in marketable fruit weight across successive harvests reflect the shifting source-sink balance as new fruit cohorts compete with maturing fruits for a finite pool of photosynthate.

Weight of Non-Marketable Fruit per Harvest

The weight of non-marketable fruit was significantly affected by harvest period based on the Greenhouse-Geisser correction ($p = 0.024$, partial $\eta^2 = 0.209$). The main effect of treatment was not significant ($p = 0.361$), and the interaction between harvest period and treatment was also not significant ($p = 0.790$). Polynomial contrasts for harvest period showed that only the cubic component was significant ($p = 0.003$), while the linear, quadratic, fourth-order, fifth-order, sixth-order, and seventh-order components were not significant. None of the polynomial contrasts for the interaction were significant ($p > .05$). Across treatments, T4 recorded the highest mean non-marketable fruit weight, followed by T2, T1, and T3. However, pairwise comparisons showed that none of the treatment differences were significant ($p > .05$).

Table 10. Effect of freshwater fish powder fertilizer on non-marketable fruit weight of eggplant across harvest periods

Treatment	H 1	H 2	H 3	H 4	H 5	H 6	H 7	H 8	Overall Mean
Treatment 1	0.00	41.25	0.00	33.75	0.00	0.00	0.00	20.00	11.88
Treatment 2	0.00	41.25	0.00	32.50	21.25	0.00	0.00	37.50	16.56
Treatment 3	0.00	37.50	0.00	32.50	0.00	0.00	0.00	18.75	11.09
Treatment 4	16.25	60.00	63.75	0.00	26.25	13.75	0.00	42.50	27.81

Within-measurement	p-Value	η²	Linear	Quadratic	Cubic	Order 4	Order 5	Order 6	Order 7
Mauchly's Test	<0.001***	0.551							
Harvest periods	0.024*	0.21	0.32^{ns}	0.67^{ns}	0.003**	0.69^{ns}	0.07^{ns}	0.12^{ns}	0.48^{ns}
Harvest periods * Treatment	0.79^{ns}	0.14	0.76^{ns}	0.98^{ns}	0.84^{ns}	0.78^{ns}	0.94^{ns}	0.15^{ns}	0.44^{ns}
Between-treatment	**p-Value**	**η²**							
Treatment	0.36^{ns}	0.226							

Means in the overall mean column followed by the same letter are not significantly different based on Tukey HSD at the 5% level. η^2 = partial eta squared; ns = not significant; * = significant at $p \leqslant 0.05$; ** = significant at $p \leqslant 0.01$; *** = significant at $p \leqslant 0.001$. Greenhouse-Geisser correction was applied when the sphericity assumption was violated

The nonsignificant treatment effect indicates that FFPF application did not significantly alter non-marketable fruit weight relative to the unfertilized control. This finding suggests that the improvements in vegetative growth and marketable fruit yield observed under fertilized treatments were not accompanied by a significant increase in non-marketable yield. The numerical ranking, with the no-fertilizer control (T4) recording the highest non-marketable fruit weight and the highest FFPF dose (T3) recording the lowest, suggests a possible tendency for FFPF to reduce rather than increase non-marketable fruit production. However, this pattern did not reach statistical significance. Nothmann and Rylski (1983) demonstrated in eggplant that basal fruits were heavier than additional fruits, and that while the presence of additional fruits did not affect the weight of basal fruits, the presence of basal fruits suppressed the development of additional fruits, resulting in smaller and more frequently unmarketable distal fruits. These findings agree with the present results because non-marketable fruit production in eggplant may arise primarily from internal sink competition and fruit positional effects rather than fertilizer treatment, explaining why FFPF rate did not significantly change non-marketable fruit weight across the cropping period. Ho (1996) concluded in tomato that fruit growth is determined mainly by sink strength and competition among developing fruits for assimilates, with fruit expansion rate affected by assimilate supply, temperature, and water relations. These findings further support the present results because when assimilate competition intensified across successive harvests, some fruits may have failed to develop properly and became non-marketable, but this competitive dynamic was common to all treatments and was not systematically modified by FFPF application.

The cubic polynomial structure of the harvest-period effect (p = 0.003), with all other trend components nonsignificant, indicates that temporal variation in non-marketable fruit weight followed a three-phase oscillatory pattern rather than a directional trend. This cubic pattern reflects episodic fluctuations in source-sink balance across the harvest sequence, where peaks in non-marketable fruit weight occurred at specific points in the cropping timeline and were separated by periods of lower non-marketable yield.

The low potassium content of FFPF (0.168% K_2O) remains relevant as a background factor in interpreting fruit quality outcomes. Arquero et al. (2006) demonstrated in olive cuttings that potassium starvation caused dehydration of plant parts, reduced growth, impaired water-use efficiency, and compromised the ability of plants to regulate stomatal closure under water stress, which are processes linked to turgor-dependent fruit cell expansion and osmotic adjustment during fruit filling. These findings suggest that the low potassium supply across FFPF treatments may have predisposed developing fruits to suboptimal turgor regulation, potentially contributing to occasional fruit malformation or undersizing. However, because all fertilized treatments shared limited potassium input, and because the no-fertilizer control numerically recorded the greatest non-marketable fruit weight, any potassium-related developmental limitation did not produce statistically significant differences in non-marketable fruit weight among treatments. This finding indicates that the primary drivers of non-marketable fruit production in the present study were developmental and competitive rather than fertilizer-rate dependent.

Total Harvest Yield

Total yield was significantly affected by treatment ($p = 0.020$), with a large effect size ($\eta^2 = 0.548$). The Welch test also confirmed a significant treatment effect ($p = 0.022$). Treatment 3 recorded the highest mean total yield, followed by Treatment 2, Treatment 1, and Treatment 4. Pairwise comparisons showed that Treatment 3 produced a significantly higher total yield than Treatment 4 ($p = .013$), while the remaining treatment comparisons were not significant ($p > .05$).

Table 11. Effect of freshwater fish powder fertilizer on total harvest yield of eggplant

Treatment	Total yield (g)
Treatment 1	3138.75 ± 793.52^{ab}
Treatment 2	3622.5 ± 1342.10^{ab}
Treatment 3	4622.50 ± 1465.62^{a}
Treatment 4	1739.50 ± 405.92^{b}
p-Value	0.020*
Eta-squared	0.58

Means and standard deviations followed by the same letter are not significantly different based on Tukey HSD at the 5% level. Total harvest yield was analyzed using one-way ANOVA. The Welch test was also used to confirm the treatment effect. η^2 = eta squared.

The superior performance of Treatment 3 may be attributed to improved nutrient availability that supported vegetative growth and reproductive development. Dubey et al. (2021) emphasized that nitrogen is essential for amino acid synthesis, protein formation, chlorophyll production, enzymatic activity, and crop growth. In the present study, the higher total yield under Treatment 3 may be associated with improved nitrogen-supported source capacity and reproductive sink activity. However, because Treatment 3 differed significantly only from Treatment 4 and not from Treatments 1 or 2, this result should be interpreted as a treatment-specific advantage rather than evidence of a strictly linear improvement with increasing FFPF level.

Phosphorus may also have contributed to the yield response under Treatment 3. Carstensen et al. (2018) showed that phosphorus deficiency can inhibit ATP synthase activity, disrupt photosynthetic electron transport, and reduce CO_2 fixation, thereby limiting assimilate production for growth and reproduction. The higher mean total yield in Treatment 3 may indicate that this treatment provided a more favorable nutrient condition for maintaining photosynthetic activity and assimilate supply during fruit development. Nevertheless, because the other pairwise comparisons were not significant, Treatments 1 and 2 cannot be considered statistically inferior to Treatment 3.

The yield advantage of Treatment 3 is also consistent with the source-sink framework of fruit production. Zhang et al. (2005) reported that assimilate availability during early fruit development is important for cell division, fruit growth, and final fruit size. In the present study, Treatment 3 may have improved assimilate availability during fruit development, which could explain its higher cumulative yield compared with Treatment 4. Similarly, Ho (1996) explained that fruit yield is influenced by source supply, sink strength, assimilate import, water relations, and metabolic activity within developing fruits. The significantly higher yield of Treatment 3 than Treatment 4 suggests that Treatment 3 may have provided a more favorable balance between nutrient supply, vegetative capacity, and reproductive demand.

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Soil Chemical Properties After Crop Harvesting

To assess treatment effects on soil chemical properties, change scores were computed for each replicate by subtracting the common before-planting baseline value from the corresponding after-harvest measurement. A composite soil sample was analyzed before planting to establish the initial soil chemical condition of the experimental area. The baseline values were pH = 4.96, N = 0.848%, P = 2.6 ppm, and K = 272 ppm. After crop harvesting, soil samples were analyzed per treatment replicate. Because the pre-planting values represented a common baseline rather than replicate-level baseline measurements, analysis of covariance was not appropriate. Therefore, one-way analysis of variance (ANOVA) was performed on the change scores for each soil parameter. Levene's test confirmed homogeneity of variances for all four parameters ($p = 1.000$), satisfying the equal-variance assumption of one-way ANOVA.

Table 12. Effect of freshwater fish powder fertilizer on soil chemical properties of eggplant after crop harvesting

Treatment	pH	Nitrogen	Phosphorus	Potassium
Treatment 1	-0.63	-0.26	34.70	51.00
Treatment 2	-0.58	-0.56	25.10	73.00
Treatment 3	-0.56	-0.34	52.10	86.00
Treatment 4	-0.34	-0.27	10.90	94.00
p-Value	0.031*	<0.001***	<0.001***	0.004**
Eta-squared	0.65	0.898	0.997	0.80

Means followed by the same letter are not significantly different based on Tukey HSD at the 5% level. η^2 = eta squared; ns = not significant; * = significant at $p \leqslant 0.05$; ** = significant at $p \leqslant 0.01$; *** = significant at $p \leqslant 0.001$

Soil pH

The mean pH change scores were −0.63, −0.58, −0.56, and −0.34 for T1, T2, T3, and T4, respectively. One-way ANOVA revealed a significant treatment effect on pH change ($p = 0.031$, $\eta^2 = 0.650$). Tukey HSD post hoc comparisons showed that the 10 g basal + 10 g side-dress treatment produced a significantly greater pH reduction than the no-fertilizer control ($p = 0.031$). The 15 g and 20 g treatments did not differ significantly from the control ($p = 0.072$ and $p = 0.102$, respectively), nor did the three fertilizer treatments differ significantly from one another.

The significant treatment effect on soil pH change indicates that FFPF influenced soil acidity after crop harvesting. All treatments showed a reduction in pH from the initial value of 4.96, but only the 10 g basal + 10 g side-dress treatment caused a significantly greater pH decline than the no-fertilizer control. This result suggests that FFPF decomposition may have contributed to soil acidification, although the response was not dose-dependent because the 15 g and 20 g treatments did not differ significantly from the control or from the 10 g treatment.

Soil Nitrogen (N)

The mean N change scores were −0.26%, −0.56%, −0.34%, and −0.27% for T1, T2, T3, and T4, respectively. One-way ANOVA indicated a highly significant treatment effect ($p < 0.001$, $\eta^2 = 0.898$). Tukey HSD comparisons showed that the 15 g basal + 10 g side-dress treatment experienced a significantly greater N reduction than the 10 g treatment ($p < 0.001$), the 20 g treatment ($p = 0.003$), and the no-fertilizer control ($p < 0.001$). The remaining three treatments, 10 g, 20 g, and no-fertilizer, did not differ significantly from one another in N change (all $p > 0.278$).

The decline in soil nitrogen after harvest is plausible because organic nitrogen from fish-derived fertilizer must first be decomposed and mineralized before becoming available to plants. Grzyb et al. (2021) explained that nitrogen in soil exists in multiple forms and is transformed mainly by microbial processes such as ammonification, nitrification, and immobilization. Ji (2013) and Hayatsu et al. (2021) likewise emphasized that soil nitrogen cycling is driven by microbial processes, including mineralization, nitrification, denitrification, and related transformations. Therefore, the post-harvest nitrogen level measured in the present study represents the net result of nitrogen release from FFPF, plant uptake, microbial immobilization, and possible nitrogen losses.

The larger nitrogen decline in the 15 g treatment may indicate stronger synchronization between nitrogen release and crop uptake at this rate. The 15 g treatment may have released nitrogen in a form and timing that was efficiently absorbed by the crop, leaving less residual nitrogen in the soil after harvest. This explanation is more defensible than claiming that the 15 g treatment depleted soil nitrogen simply because of fertilizer rate, since the 20 g treatment did not show the greatest nitrogen decline.

The present nitrogen result partly differs from Pranckietienė et al. (2013), who found that fish bone application increased mineral, nitrate, and ammonium nitrogen in tested soils, and from Vaisvalavičius et al. (2021), who reported increased total and mineral nitrogen after fish bone powder application, particularly at the higher application rate. The difference may be due to the timing of soil sampling. Those studies emphasized nutrient accumulation in soil following amendment application, while the present study measured nitrogen after crop growth and harvest. By that point, much of the mineralized nitrogen may already have been absorbed by eggplant plants or transformed through microbial processes. Thus, the nitrogen decline does not contradict the growth-promoting effect of FFPF; rather, it suggests that nitrogen supplied or stimulated by FFPF was actively used during crop development.

Soil Phosphorus (P)

All treatments recorded positive P change scores: 34.70, 25.10, 52.10, and 10.90 ppm for the 10 g, 15 g, 20 g, and no-fertilizer treatments, respectively. One-way ANOVA revealed a highly significant and very large treatment effect ($p < 0.001$, $\eta^2 = 0.997$). Tukey HSD post hoc tests showed that all four treatment groups differed significantly from one another (all $p < 0.001$), with the 20 g treatment recording the greatest P increase, followed by the 10 g treatment, the 15 g treatment, and the no-fertilizer control. Each treatment formed its own homogeneous subset.

This finding is strongly supported by previous studies on fish-bone fertilizer. Pranckietienė et al. (2013) reported that fish bone application significantly increased available phosphorus in both tested soils. Vaisvalavičius et al. (2021) similarly found that fish bone powder significantly increased available phosphorus in soil. These findings agree with the present result because FFPF contains a high phosphorus level, making it a plausible source of residual soil phosphorus after crop harvesting.

The increase in phosphorus is especially important because the initial soil was acidic. In acid soils, phosphorus is commonly fixed by aluminum and iron, reducing its availability to plants. Ch'Ng et al. (2014) reported that soluble inorganic phosphorus in acid soils is fixed by aluminum and iron, but organic amendments can alter soil chemical conditions and improve phosphorus availability. Iyamuremye et al. (1996) also found that manure and organic residues increased available and mineralizable phosphorus fractions in acid soils. These studies support the present finding that organic fertilizer materials can increase measurable phosphorus availability even under acidic conditions.

However, phosphorus behavior under organic amendments is not always straightforward. Mabagala and Mng'ong'o (2022) emphasized that organic matter can either increase or decrease phosphorus availability depending on mineralization, sorption, desorption, soil type, and the nature of phosphorus-binding surfaces. Ch'Ng et al. (2016) further showed that organic amendments may improve phosphorus availability but may also increase phosphorus loss under some conditions because of lower sorption strength. Therefore, while the strong phosphorus increase under the 20 g treatment indicates a beneficial residual fertility effect, repeated FFPF application should be monitored to avoid excessive phosphorus accumulation.

The nonlinear ranking of phosphorus increase, where the 10 g treatment exceeded the 15 g treatment, should not be ignored. This pattern may reflect differences in crop phosphorus uptake, microbial mineralization, soil fixation, or experimental variability. Therefore, the result supports the conclusion that FFPF increased soil phosphorus, especially at the 20 g rate, but it does not support a perfectly linear phosphorus response across all fertilizer rates.

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Soil Potassium (K)

Mean K change scores were 51, 73, 86, and 94 ppm for the 10 g, 15 g, 20 g, and no-fertilizer treatments, respectively. One-way ANOVA showed a significant treatment effect ($p = 0.004$, $\eta^2 = 0.799$). Tukey HSD comparisons revealed that the 10 g treatment had a significantly smaller K increase than the 20 g treatment ($p = 0.011$) and the no-fertilizer control ($p = 0.003$). No other pairwise comparisons reached significance (all $p > 0.102$), and Tukey's homogeneous subsets placed the 10 g treatment in a distinct lower subset, while the 15 g, 20 g, and no-fertilizer treatments overlapped in the higher subset.

The result is reasonable because FFPF appears to be richer in nitrogen and phosphorus than potassium. Therefore, even if FFPF supplied some potassium, its potassium contribution was likely limited compared with its nitrogen and phosphorus contribution. Previous fish-bone fertilizer studies show that fish-derived amendments can increase potassium under some conditions. Pranckietienė et al. (2013) reported positive effects of fish bone application on available potassium in both medium heavy loam and sandy loam soils, while Vaisvalavičius et al. (2021) found that fish bone powder increased available potassium in tested soil. The present result partly agrees with those studies because potassium increased after harvest, but the increase was not clearly proportional to FFPF rate.

The unexpectedly high potassium increase in the no-fertilizer control may be explained by lower crop uptake and lower biomass production. Because the control plants generally produced weaker vegetative growth and lower yield, they likely removed less potassium from the soil through plant uptake and harvested fruit. In contrast, fertilized treatments supported stronger growth and yield, which may have increased potassium absorption and removal. Thus, higher residual potassium in the control does not necessarily indicate better soil fertility; it may indicate lower crop extraction of potassium.

Potassium also exists in multiple soil pools, which complicates interpretation. Harinkhere et al. (2015) explained that soil potassium occurs as water-soluble, exchangeable, non-exchangeable, and lattice potassium, with only the soluble and exchangeable forms being available to plants. Moody and Bell (2006) showed that potassium uptake may draw not only from exchangeable potassium but also from fixed or slowly available potassium pools, depending on soil type. Hinsinger et al. (2020) further explained that plant roots can deplete rhizosphere potassium and stimulate desorption or release of non-exchangeable potassium from minerals. These studies support the interpretation that the measured post-harvest potassium changes may reflect redistribution among soil potassium pools, not simply fertilizer input.

Organic residues may also affect potassium release. Li et al. (2014) found that potassium in rice straw residues was released rapidly, with most potassium released early during decomposition. Ranjbar and Jalali (2012) similarly reported rapid potassium release from decomposing organic residues, while Andrews et al. (2021) emphasized that potassium in plant materials is highly mobile and readily solubilized. Although FFPF is not a plant residue, these studies are relevant because they show that potassium behavior in organic materials can be rapid, mobile, and strongly affected by water movement and soil exchange processes. Therefore, the post-harvest potassium increase across all treatments may reflect a combination of potassium release, exchange reactions, crop uptake differences, and soil buffering.

The potassium result suggests that FFPF should not be considered a complete potassium fertilizer. Its use may improve crop growth through nitrogen and phosphorus supply, but stronger growth may also increase potassium demand. If FFPF is used repeatedly, potassium should be monitored because high crop uptake without sufficient potassium replacement can eventually deplete plant-available potassium pools.

VI. CONCLUSIONS

Based on the findings of the study, the following conclusions were drawn:

1. Freshwater fish powder fertilizer (FFPF) was effective in improving the growth and yield of eggplant (Solanum melongena L.), particularly in vegetative development and selected yield components. Among the treatments evaluated, Treatment 3, consisting of 20 g basal application + 10 g side-dress application, gave the best overall performance.

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2. FFPF did not significantly influence reproductive timing, as flowering and first harvest were not accelerated by fertilizer application. Its main contribution was therefore in improving plant growth, fruit development, marketable yield, and total fruit yield rather than shortening the production period.
3. The study further concludes that the effects of FFPF were not consistently dose-dependent. While Treatment 3 was the best-performing treatment, lower FFPF rates also produced improvements in some parameters and were not always statistically different from Treatment 3.
4. Overall, FFPF can be considered a beneficial organic fertilizer for eggplant production, with Treatment 3 as the most suitable rate among the treatments tested. However, its continued use should be supported by soil monitoring because post-harvest soil results indicated changes in soil pH and nutrient levels.

VII. RECOMMENDATIONS

Freshwater fish powder fertilizer (FFPF) may be used as an organic fertilizer for eggplant production, with Treatment 3, consisting of 20 g basal application + 10 g side-dress application, recommended when the goal is to maximize growth and yield.

1. Lower FFPF rates may be considered when fertilizer supply or production cost is a concern, especially since the highest rate was not statistically superior to the lower rates in all parameters.
2. FFPF should not be used primarily to induce earlier flowering or earlier harvesting, as its benefit is more appropriate for improving crop growth and yield performance.
3. Regular soil testing is recommended when FFPF is used continuously. Soil pH, nitrogen, phosphorus, and potassium should be monitored to prevent nutrient imbalance, soil acidification, or excessive nutrient accumulation.
4. For long-term use, FFPF may be combined with potassium supplementation and, where necessary, liming materials to maintain soil fertility and reduce acidity risks.
5. Future studies should evaluate FFPF across different seasons, soil types, and application rates. Economic analysis should also be included to determine whether the recommended rate is cost-effective for farmers.

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