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Enhancing Bird's Eye Chili (*Capsicum frutescens*) Productivity Through Combined Application of Eco-Enzyme and *Trichoderma viride*

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Abstract. Bird's eye chili (*Capsicum frutescens* L.) is a high-value horticultural crop, yet yields in Indonesia remain low due to long-term use of chemical fertilizers, which reduce soil fertility. Organic fertilizer alternatives, such as eco-enzyme and *Trichoderma viride,* offer potential for sustainable agriculture. This research aimed to study the impact of eco-enzyme and *T. viride*, applied individually and in combination, on the growth and yield of Bird's eye chili, as well as on soil N, P, K, organic carbon, and IAA levels. The study employed a Completely Randomized Design (CRD) with four treatments: control, eco-enzyme, *T. viride*, and a combination of eco-enzyme and *T. viride*, each with eight replications. The research was conducted in a polybag over 20 weeks. Parameters observed were plant height, leaf number, root length, number of flowers and fruits, fruit weight, and soil N, P, K, C-organic, and IAA. Compared with the control treatment, the application of eco-enzyme and *T. viride* improved several growth and soil quality parameters. The combined treatment increased vegetative growth and enhanced soil N, P, K, and IAA contents, whereas *T. viride* alone produced the highest fruit yield. These results suggest that eco-enzyme and *T. viride* can be used as biological inputs to improve chili production while helping maintain soil fertility and reduce dependence on chemical fertilizers. The findings are relevant to SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land), particularly regarding sustainable food production, resource recycling, and soil conservation.

Keywords: Bird's eye chili; eco-enzyme; plant growth; plant yields; *Trichoderma viride*

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INTRODUCTION

Bird's eye chili (*Capsicum frutescens* L.) is one of Indonesia's most promising horticultural export commodities, which possesses high economic value (Maulana et al., 2025). Despite its potential, the production of bird's eye chili in Indonesia remains low, even as consumer demand continues to increase each year (Maulana et al., 2025). To meet this growing demand, many farmers rely heavily on chemical fertilizers. However, prolonged use of chemical fertilizers may degrade soil fertility—physically, chemically, and biologically (Prakash, 2023)—which ultimately leads to suboptimal plant growth (Afra et al., 2022).

As a sustainable alternative, the use of organic fertilizers such as eco-enzyme has gained attention. Eco-enzymes can improve soil conditions, enhance nutrient availability for plants, maintain soil fertility, and stimulate the growth of beneficial soil microorganisms (Azuhro et al., 2024). They contain microorganisms such as lactic acid bacteria and acetic acid bacteria (Tallei et al., 2023) as well as several bacterial species capable of producing indole acetic acid (IAA) (Meitiniarti et al., 2025). These microorganisms play an essential role in decomposing organic matter and converting it into plant nutrients such as nitrogen (N), phosphorus (P), potassium (K), and organic carbon (C-organic). Supporting this, studies by Fadlilla et al. (2023) and Salsabila & Winarsih (2023) confirmed that eco-enzymes contain NPK elements and C-organic. Meitiniarti et al. (2024) also demonstrated that eco-enzymes contain enzymes such as cellulase, urease, and amylase, which play key roles in the decomposition of organic materials and nutrient availability for plants. The application of eco-enzymes as fertilizers has been shown to enhance soil fertility and increase chili plant resistance to pests (Kesmayanti et al., 2025).

Microorganisms in the rhizosphere also play a significant role in promoting plant growth by supplying nutrients, producing antibiotic compounds, and synthesizing growth hormones such as IAA (Backer et al., 2018). *Trichoderma viride* is one such beneficial fungus known for its ability to produce IAA (Zehra et al., 2017)and improve the availability of phosphorus, potassium, and soil nutrients (Santi et al., 2019). Previous studies have demonstrated that the application of *T. viride* to chili plants enhances growth, yield, and soil fertility (Vij et al., 2024; Nirosha et al., 2018).

Considering these findings, both eco-enzyme and *T. viride* hold great potential to improve plant growth and productivity. However, research on the combined use of eco-enzyme and *T. viride* to enhance bird's eye chili productivity remains limited. Therefore, this study aims to analyze the effects of eco-enzyme and *T. viride*—applied individually and in combination—on soil nutrient content (N, P, K), soil organic carbon, and IAA levels, as well as on vegetative growth and yields of bird's eye chili. The combined application of eco-enzyme and *Trichoderma viride* will synergistically improve soil nutrient content, increase IAA levels, and enhance the vegetative growth and yield of bird's eye chili compared to their individual applications.

METHODS

The research and IAA testing were conducted at the Biology Laboratory of Satya Wacana Christian University (UKSW), Salatiga, Indonesia, from March to May 2024. The analysis of N, P, K, and organic carbon contents was carried out at CV. Chem-Mix Pratama (Yogyakarta, Indonesia). The study was designed using a Completely Randomized Design (CRD) with four treatments and eight replications: control, *T. viride*, eco-enzyme, and a combination of *T. viride* + eco-enzyme. The experiment lasted 20 weeks, with treatments applied at the start. Plant maintenance, including regular watering, was carried out throughout the experiment period. Samples were collected weekly for data observation. Growth parameters were recorded weekly, while yield data were measured at the end of the study.

Preparation of Growing Media and Chili Seedlings. The planting medium, purchased from Kopeng, was first sterilized in an autoclave at 121°C for 2 hours. Sterilization was repeated for three consecutive days at 24-hour intervals, which is in accordance with research by Salsabila & Winarsih (2023). A total of 3.5 kg of sterile planting medium was placed in 25 cm × 25 cm polybags, with one seedling planted per polybag. A total of 32 polybags were prepared according to the treatments. One-month-old bird's eye chili seedlings, which were purchased from the Kopeng area, were cleaned with water to ensure that no previous medium contaminated the new planting medium.

Application of the Eco-enzyme and *T. viride*. The eco-enzyme used in this study was a diluted solution (30 mL dissolved in 1 L of water). Eco-enzyme was prepared from a mixture of fruit and vegetable waste including orange peel, banana, papaya, watermelon, mustard greens, and cabbage. The fruit and vegetable wastes were mixed in approximately equal proportions based on availability, without a fixed ratio among the types. The organic materials were chopped into small pieces (about 1-2 cm) and mixed with molasses and water in a 3:1:10 (organic waste: molasses: water) ratio. The mixture was placed in an airtight plastic container and kept at ambient tropical temperature (approximately 27–30 °C) for 3 months of fermentation, with periodic venting to release gas pressure. After three months of fermentation, the mixture was filtered through a fine mesh cloth, and the liquid fraction was separated from the solid residue and used as the eco-enzyme. The *T. viride* inoculum used in this study was obtained from the culture collection of Universitas Kristen Satya Wacana, Indonesia. *T. viride* was applied in the form of spores harvested from 48-hour-old cultures on Potato Dextrose Agar (PDA) medium. According to the treatment design, eco-enzyme (15 mL/polybag) and *T. viride* (11.25×10^7 spores/polybag) were incorporated into the planting medium immediately before transplanting the chili seedlings.

Parameter Determination. The determination of growth parameters was divided into two categories: vegetative and generative growth. The vegetative growth parameters included plant height, number of leaves, root length, fresh weight, and dry weight. The measured generative growth parameters were the number of flowers, the number of fruits, and the weight of fruits. Additional parameters assessed in this study included: IAA levels in the soil and eco-enzymes, determined using the colorimetric method (Farma et al., 2022); total soil N content, measured using the Kjeldahl method; available soil P, analyzed using the UV-V spectrophotometric method (Rahmawati & Widyasari, 2022); soil K levels, determined using the gravimetric method (Hicks, 2025); photosynthetic pigment (chlorophyll and carotenoids), quantified using the dimethyl sulfoxide (DMSO) method (Rasyidi et al., 2024), and soil pH, measured using a digital pH meter (FAO (Food and Agriculture Organization of United Nations), 2021)

Statistical Analysis of Data. All data obtained were tested for homogeneity of variance and normality prior to analysis of variance (ANOVA). If significant differences were detected among treatments, a Least Significant Difference (LSD) test at the 5% significance level was applied to separate means and identify the best-performing treatment. Statistical analyses were performed using SAS software, version 9 (SAS Institute Inc., Cary, NC, USA).

RESULTS AND DISCUSSION

The Effects of Treatments on Vegetative Growth

The vegetative growth of Bird's Eye Chili plants showed varied responses to the treatments applied. Among the four treatments, the *T. viride* inoculation resulted in the highest vegetative growth (Table 1). This increase might be attributed to elevated nitrogen (N) and phosphorus (P) levels, even though their concentrations were not the highest among all treatments (Table 2).

According to Prakash (2023), N and P fertilization enhances vegetative growth. The soil IAA content was also relatively higher under *T. viride* treatment, suggesting that *T. viride* acts as an IAA producer that supports shoot and root elongation. This tendency is consistent with the IAA levels presented in Figure 1.

The differences in vegetative growth among treatments were also visually evident at the end of the experimental period (Figure 2). Plants treated with *T. viride* showed more vigorous growth, characterized by greater plant height, root development, and biomass accumulation compared with the control. The eco-enzyme and combined treatments also improved plant performance relative to the control, supporting the quantitative results presented in Table 1.

Table 1. Effects of Treatment on the Growth of Bird's Eye Chili Plants

Treatment	Plant Height (cm)	Number of Leaves	Root Length (cm)	Fresh Weight (g)	Dry Weight (g)
Control	23.4 ± 3.14^{d}	23.6 ± 2.92^{c}	11.8 ± 1.81^{d}	6.0 ± 2.26^{d}	1.4 ± 0.26^{c}
T. viride	80.1 ± 5.84^{a}	44.0 ± 7.93^{b}	26.5 ± 3.81^{a}	26.5 ± 8.61^{a}	6.8 ± 2.32^{a}
Eco-enzyme	48.8 ± 6.83^{c}	74.9 ± 10.37^{a}	16.6 ± 2.06^{c}	14.1 ± 5.40^{c}	3.3 ± 1.03^{b}
TV+Eco-enzyme	64.7 ± 5.77^{b}	70.1 ± 11.83^{a}	20.5 ± 2.63^{b}	25 ± 5.62^{ab}	6.3 ± 1.64^{a}

Note: Numbers followed by the same letter are not significantly different based on the 5% LSD test.

Table 2. Effects of treatment on NPK and C-organic Content in Soil Media Before and After Treatment

Soil	Treatment	The content of			
		N (%)	P (%)	K (%)	C-organic (%)
Before the experiment	C	0.07 ± 0.00^{c}	0.16 ± 0.002^{b}	0.31 ± 0.003^{d}	1.40 ± 0.02^{d}
	TV	0.08 ± 0.00^{b}	0.16 ± 0.001^{a}	0.40 ± 0.002^{b}	1.65 ± 0.03^{c}
	EE	0.09 ± 0.00^{a}	0.15 ± 0.001^{c}	0.44 ± 0.002^{a}	2.59 ± 0.02^{a}
	TV+EE	0.08 ± 0.00^{b}	0.15 ± 0.001^{c}	0.35 ± 0.003^{c}	2.06 ± 0.02^{b}
After the experiment	K	0.17 ± 0.00^{d}	0.58 ± 0.000^{d}	0.51 ± 0.005^{d}	1.44 ± 0.02^{d}
	TV	0.22 ± 0.01^{c}	0.67 ± 0.001^{a}	0.72 ± 0.003^{a}	3.29 ± 0.03^{a}
	EE	0.25 ± 0.01^{b}	0.64 ± 0.001^{b}	0.64 ± 0.009^{b}	2.55 ± 0.04^{c}
	TV+EC	0.34 ± 0.02^{a}	0.63 ± 0.001^{c}	0.56 ± 1.89^{c}	2.68 ± 0.06^{b}

Note: Numbers followed by the same letter are not significantly different based on the 5% LSD test. C = control, TV = *T. viride*, EE = eco-enzyme, and TV + EE = *T. viride* + eco-enzyme.

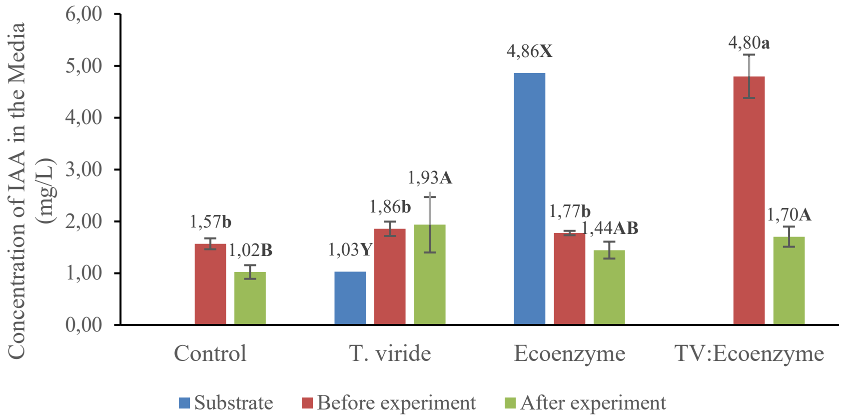


Figure 1. Concentration of Indole-3-Acetic Acid (IAA) in the Medium and Soil as Affected by Treatments

Note: Numbers followed by the same letter are not significantly different based on the 5% LSD test. Uppercase letters (A, B, C) were significantly different before the experiment, whereas lowercase letters (a, b, c) indicate comparisons after the experiment. X = subtraction test of eco-enzyme; Y = subtraction test of *T. viride*.

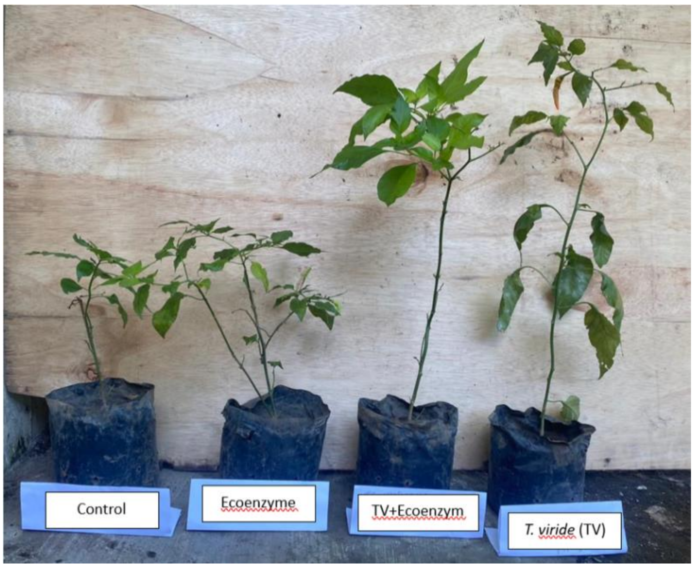


Figure 2. Representative Bird's Eye Chili Plants from the Control, Eco-enzyme (EE), Combined *T. viride* + eco- enzyme (TV+EE), and *T. viride* (TV) Treatments After 20 Weeks of Cultivation.

The results of this study indicate that *T. viride* treatment enhanced plant biomass accumulation, as reflected in the highest recorded fresh and dry weights (Table 1). This growth-promoting effect is likely associated with the ability of *T. viride* to synthesize indole-3-acetic acid (IAA), which was also detected at elevated levels in the culture medium (Figure 1). The increased IAA concentration may have stimulated cell division and elongation, thereby promoting more vigorous vegetative growth. Similar findings were reported by Backer et al. (2018), who found that *T. viride* and other plant-growth-promoting fungi enhance plant development through IAA synthesis. Furthermore, IAA has been shown to improve soil structure and facilitate nutrient uptake (Wei et al., 2024), which may have further contributed to the enhanced biomass accumulation observed in this study. Collectively, these findings indicate that *T. viride* promotes plant growth through a multifaceted mechanism involving both hormonal regulation and improved soil-plant interactions.

High dry weight typically indicates optimal metabolic efficiency and photosynthetic activity (Morales et al., 2020). Similarly, increased root length, as seen in the *T. viride* treatment, supports efficient water and nutrient uptake (Afra et al., 2023) (Table 1). The increase in vegetative organs biomass in the *T. viride* treatment is likely the result of a synergistic effect between hormonal activity, improved nutrient absorption, and optimal root growth (Zehra et al., 2017)

Among the vegetative growth parameters, the number of leaves was highest in the combination of *T. viride* and eco-enzyme treatment, and in the single eco-enzyme treatment, with no significant difference between them. Eco-enzymes are natural bio-solutions produced through the fermentation of fruit and vegetable peels with sugar, forming a complex mixture of enzymes and organic acids. Organic acids such as acetic acid and lactic acid have been identified as key components of eco-enzymes (Sembiring et al., 2021). These acids can act as antimicrobial agents and pH regulators in the soil, thereby creating a favorable environment for beneficial microorganisms and plant growth (Tallei et al., 2023). The enzymatic activity also helps decompose organic matter and release essential nutrients such as phosphorus and potassium, thereby increasing crop yields. Therefore, eco-enzymes not only improve soil fertility ecologically but also support optimal plant growth and effectively increase harvest yields (Benny et al., 2023).

In the combination of *T. viride* and eco-enzyme treatments, nitrogen availability was also the highest among all treatments. The concurrent elevation of N and IAA levels is believed to have contributed to the increase in leaf number. The high nitrogen availability and IAA concentration under this treatment likely acted synergistically to promote cell division and leaf differentiation (Morales et al., 2020).

The accumulation of photosynthetic pigments further supported the increase in plant biomass (Table 3). Although chlorophyll *a* level in the *T. viride* and eco-enzyme treatments was not significantly different from the control, carotenoid levels were markedly higher in the eco-enzyme and combination treatments.

The increase in chlorophyll content generally reflects improved light-harvesting efficiency for photosynthesis, whereas carotenoids protect leaves from oxidative stress (Nazari et al., 2024). Chlorophyll synthesis, however, is primarily influenced by nitrogen availability, environmental conditions, and the physiological status of the leaves, rather than the leaf number itself (Martins et al., 2023). Consistent with these findings, Nazari et al. (2024) reported that while *T. viride* application increases IAA levels, chlorophyll synthesis remains strongly dependent on adequate nitrogen supply.

The Effects of Treatments on Generative Growth

The generative growth of chili plants varied significantly among treatments. The *T. viride* treatment resulted in the highest number of flowers (6.75), fruits (4.38), and fruit weight (4.12 g) (Table 4). In addition, flowering and fruiting also occurred earlier, in the 7th and 8th weeks, respectively (Figure 3), indicating an accelerated transition to the generative phase. This acceleration is closely related to the ability of *T. viride* to produce the IAA hormone, in stimulating cell division, promotes the differentiation of reproductive organs, and expands the root nutrient absorption zone (Backer et al., 2018).

Table 3. Effects of Treatment on Photosynthetic Pigment Content of Bird's Eye Chili Plants

Treatment	Photosynthetic Pigments Content (mg/L)			
	Chlorophyll a	Chlorophyll b	Total Chlorophyll	Carotenoid
Control	5.85 ± 1.32^{c}	2.40 ± 0.55^{ab}	7.98 ± 0.91^{d}	1.68 ± 0.40^{c}
T. viride	11.96 ± 0.30^{b}	1.73 ± 0.21^{b}	13.33 ± 0.47^{c}	2.26 ± 0.17^{b}
Eco-enzyme	13.18 ± 1.18^{b}	2.48 ± 0.21^{ab}	15.23 ± 1.31^{b}	2.79 ± 0.11^{a}
TV+Eco-enzyme	15.09 ± 0.47^{a}	2.98 ± 0.72^{a}	17.57 ± 1.04^{a}	2.89 ± 0.18^{a}

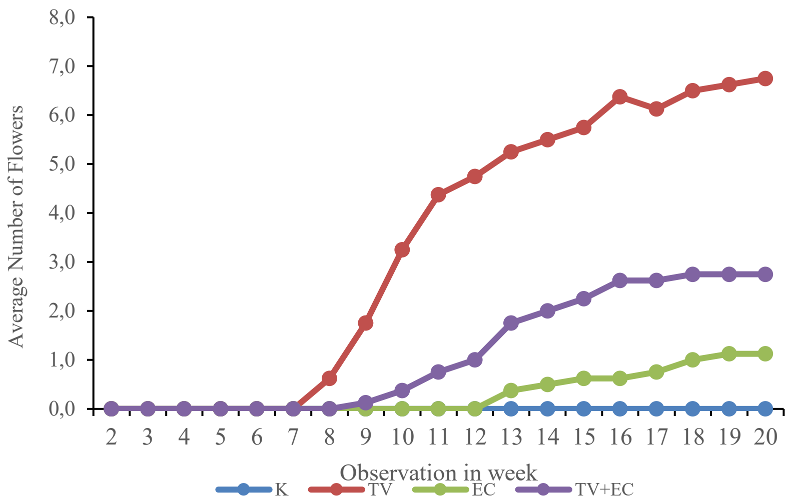
Note: Numbers followed by the same letter are not significantly different based on the 5% LSD test.

Table 4. Generative Growth

Treatment	Number of Flowers	Number of Fruits	Fruit Weight (g)
Control	23.4 ± 3.14^{d}	0.00 ± 0.00^{c}	0.00 ± 0.00^{c}
T. viride	80.1 ± 5.84^{a}	4.38 ± 2.20^{a}	4.12 ± 2.14^{a}
Eco-enzyme	48.8 ± 6.83^{c}	0.75 ± 1.04^{bc}	0.14 ± 0.26^{c}
TV+Eco-enzyme	64.7 ± 5.77^{b}	2.13 ± 1.81^{b}	2.10 ± 1.89^{b}

Note: Numbers followed by the same letter are not significantly different based on the 5% LSD test.

a)



b)

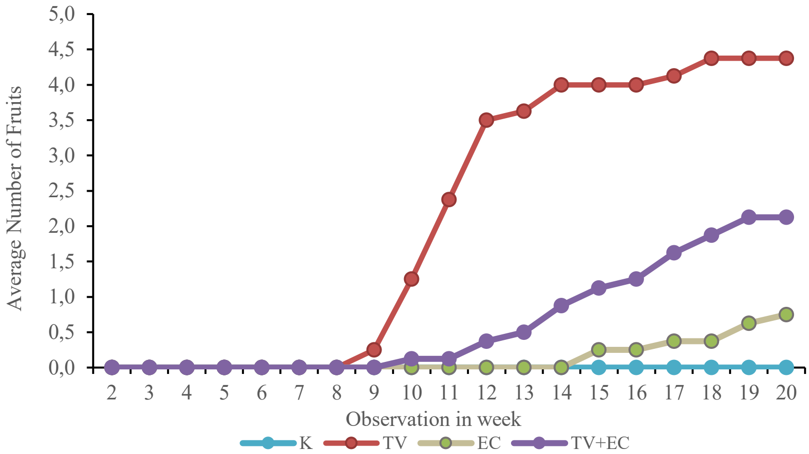


Figure 3. Average number of Flowers (a) and Fruits (b) Development in Bird's Eye Chili Plants from Week 2 to Week 20

The high soil IAA levels observed in the *T.viride* treatment (Figure 1) support the hypothesis that hormonal regulation promotes flower and fruit initiation. In addition, the increased yields are also supported by the efficient absorption of phosphorus (P) and potassium (K) (Figure 4). These two nutrients are essential for the development of generative organs (Rohcahyani et al., 2025). The high yields, reflected in the number and weight of fruits, indicated that both photosynthetic activity and the translocation of metabolic products are efficient.

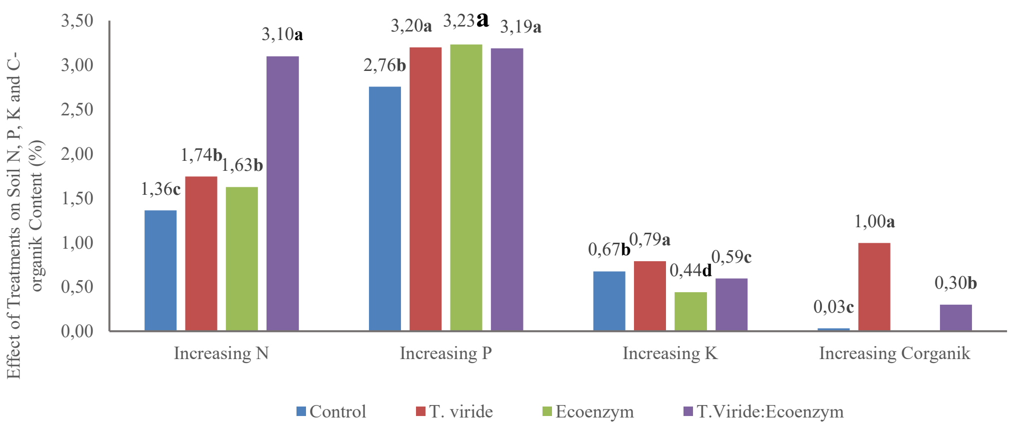


Figure 4. Effect of Treatments on Soil N, P, K, and C-Organic Content.
Note: Numbers followed by the same letter are not significantly different based on the 5% LSD test.

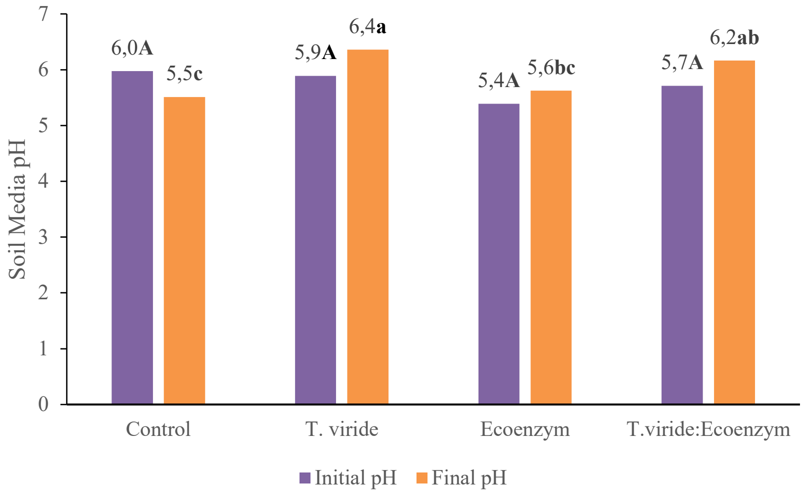


Figure 5. Effect of Treatments on Soil pH

Note: Numbers followed by the same letter are not significantly different based on the 5% LSD test. As seen in the uppercase letters (A), no significant differences were observed in the initial soil pH following treatment application, whereas lowercase letters (a, ab, bc, c) showed significant differences in the final soil pH prior to harvest.

The highest yield, based on fruit weight (4.12 g), was observed in the *T. viride* treatment and was significantly higher than those of the other treatments (Table 4). This result is consistent with the greater number of fruits observed in the *T. viride* treatment. In contrast, the combination treatment of *T. viride* and eco-enzyme resulted in lower yields, while the eco-enzyme and control treatments produced the lowest yields, with no significant difference between them. The increase in fruit weight in the *T. viride* treatment is likely associated with the increased IAA production in the planting medium, which stimulates cell division and enhances the absorption efficiency of essential nutrients such as phosphate and potassium, thereby supporting the optimal development of generative organs (Song et al., 2024).

Initial pH measurements of the planting medium (Figure 5) indicated slightly acidic conditions, with no significant variation among treatments. This indicates that although eco-enzyme solutions are known to exhibit low pH (around 3-4) (Sembiring et al., 2021), their application at low concentrations did not significantly alter soil acidity. By the end of the study, the pH of the planting medium generally increased slightly across all treatments, except the control. In treatments inoculated with *T. viride* alone or in combination with the eco-enzyme, the pH exceeded 6 (Figure 5). The final pH values remained within the optimal range (5.5–6.5) for chili cultivation, a range known to favor nutrient availability and uptake efficiency (Fimbres-Acedo et al., 2023).

Notably, this study shows that the combination of *T. viride* and eco-enzyme does not necessarily produce synergistic effects, as enhanced vegetative growth was not consistently associated with higher generative yields. This finding challenges the common assumption that combined bio-inputs always improve crop performance and highlights the importance of growth-phase-specific responses to biological amendments. Overall, these results provide practical guidance for optimizing biological inputs in chili cultivation by aligning microbial and organic amendments with specific production objectives.

This study provides novel insight into the effects of eco-enzyme and *T. viride*, applied individually and in combination, on the growth, yield, and soil characteristics of Bird's eye chili (*Capsicum frutescens* L.). Beyond its agronomic implications, this research contributes to several Sustainable Development Goals (SDGs). The improvement in chili productivity and yield supports SDG 2 (Zero Hunger) by promoting sustainable agricultural production and enhancing food security. The utilization of eco-enzyme derived from organic waste and the reduced dependence on chemical fertilizers align with SDG 12 (Responsible Consumption and Production), encouraging resource efficiency and sustainable agricultural inputs. Furthermore, the enhancement of soil nutrient status and soil biological quality supports SDG 15 (Life on Land) by fostering soil health and environmentally sustainable land management practices. These findings demonstrate the potential of biological amendments as practical tools for developing more sustainable and resilient horticultural production systems.

CONCLUSION

Based on the results of this study, it can be concluded that *T. viride* had the strongest effect on bird's eye chili performance. Plants receiving *T. viride* exhibited greater vegetative growth, higher fruit production, and improved soil nutrient status than untreated plants. Although the combination of *T. viride* and eco-enzyme increased leaf development, it did not outperform *T. viride* alone in terms of yield. These observations suggest that *T. viride* plays a major role in improving chili productivity under the conditions evaluated in this study. Additional studies for future research using different application rates and cultivation conditions are needed to determine whether the interaction between eco-enzyme and *T. viride* can further enhance productivity and support long-term soil health.

AUTHOR CONTRIBUTION STATEMENT

All authors contributed significantly to the work reported in this manuscript. SRPD conducted the research, collected and analyzed the data, and prepared the original manuscript draft. VIM and SK contributed to the conceptualization of the study, designed the research methodology, supervised the research, and critically reviewed and revised the manuscript. SP and SNH contributed to English language editing and improved the discussion of the research findings. All authors have read and approved the final manuscript.

CONFLICT OF INTEREST STATEMENT

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

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with English language editing and improve the clarity of the writing. The authors carefully reviewed and edited the output and take full responsibility for the content of this manuscript.

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