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Combination of *Mucuna bracteata* Mulch and NPK-Biofertilizer for Taro (*Colocasia esculenta* L.) Vegetative Growth

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Abstract. Taro (*Colocasia esculenta* L.) is a tuber crop with high economic value and potential as an alternative food source, yet its productivity remains low due to declining soil fertility and low organic matter content. This study aimed to evaluate the effect of *Mucuna bracteata* organic mulch combined with reduced NPK fertilizer dosage and biofertilizer application on the vegetative growth of taro. The experiment was conducted at the Experimental Garden of the Faculty of Agriculture, University of Riau, from May to August 2025 using a non-factorial Completely Randomized Design with five treatments and four replications. Observed parameters included leaf stalk length, number of leaves, leaf area, leaf area index, stem diameter, chlorophyll content, soil temperature, and soil moisture. The results indicated that 75% and 50% NPK fertilizer combined with biofertilizer and *M. bracteata* mulch produced vegetative growth comparable to that of 100% NPK fertilizer across most parameters. The use of *M. bracteata* mulch and biofertilizer reduced inorganic NPK fertilizer requirements by 25–50% without decreasing vegetative growth.

Keywords: biofertilizer; fertilizer efficiency; organic mulch; taro; vegetative growth

1. Introduction

Taro (*Colocasia esculenta* L.) is a tuberous plant in the Araceae family with high economic value because almost all its parts can be used for food, medicine, packaging, and animal feed (Habibah & Astika, 2020). Taro tubers are rich in carbohydrates, making them a potential alternative food ingredient (Estianti et al., 2024). Vegetative growth plays an important role in determining plant yield, as this phase directly contributes to the development of generative organs and tuber formation (Serly, 2015). Despite its great potential, taro production in Riau remains low and fluctuates, reaching 37.06 tons in 2023 and 22.70 tons in 2024 (Pekanbaru City Agriculture and Fisheries Service, 2025). This decline in production is influenced by environmental factors, including suboptimal soil moisture resulting from inappropriate land management.

Soil moisture is a crucial factor in supporting taro growth, so cultivation techniques that maintain stable soil temperature and moisture are essential. One effective method is using organic mulch. Mulch can improve soil aggregate structure and stability, suppress weed growth, reduce erosion, and maintain soil temperature and moisture, thus supporting optimal nutrient release for the plant. Toruan & Nurhidayah, 2017). Study Nurhadiah (2020) showed that the application of *Mucuna bracteata* at 3 kg m^{-2} produced the best growth in green mustard, with a plant height of 26.58 cm, 13.25 leaves, and a fresh weight of 0.092 kg plant^{-1}.

*Mucuna bracteata*is a ground cover plant that has high potential to be used as mulch because it is tolerant to pests and diseases, is not liked by livestock due to its phenol content, and is easily decomposed, so it quickly provides nutrients (Fatonah et al., 2015; Safitri & Hapsoh, 2017). This plant is rich in organic matter, with N 3.71%, P 0.38%, K 2.92%, Ca 2.02%, Mg 0.36%, C-organic 31.4%, and C/N ratio 8.46% (Purwasih et al., 2019). These organic materials improve the soil's physical, chemical, and biological properties, including increasing nitrogen availability, which is very important for vegetative

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growth.

Besides mulch, nutrient requirements can be met through inorganic fertilization. NPK compound fertilizer is a complete fertilizer containing nitrogen, phosphorus, and potassium, which are needed for vegetative and generative growth (Purba et al., 2021). However, excessive use of inorganic fertilizers can reduce the activity of soil microorganisms, inhibit the decomposition of organic materials, pollute the environment, and increase production costs (Herdiyanto & Setiawan, 2015). Therefore, a more efficient and sustainable fertilization system is needed.

Biofertilizer is an alternative that can improve soil fertility by containing microorganisms that increase nutrient availability through biochemical activities such as decomposition, phosphate dissolution, and increased soil microbial activity (Kusumawati, 2021; Martin et al., 2020). Cellulolytic bacteria are known to decompose organic materials more quickly. Research Hapsoh et al. (2018) found six potential cellulolytic bacterial isolates, namely *Bacillus cereus* JP6 and JP7, *Proteus mirabilis* TKKS3 and TKKS7, and *Providencia vermicola* SA1 and *Bacillus cereus* SA6. 10 mL plant^{-1} of cellulolytic bacteria-based biofertilizer was proven to increase the growth of sweet corn (Hapsoh et al., 2020), accelerate the harvest age and weight of 100 seeds in green beans (Hapsoh et al., 2023a), and has a positive effect on rice growth and yield when combined with 75% NPK and 16 t ha^{-1} solid compost (Hapsoh et al., 2023b).

The integration of *Mucuna bracteata* organic mulch, biofertilizer, and reduced NPK fertilizer dosage is an important strategy in creating an efficient and environmentally friendly taro cultivation system. This combination of technologies has the potential to increase fertilizer efficiency, improve soil quality, maintain soil moisture, and provide nutrients sustainably. Based on these considerations, this study was conducted to examine the effects of organic mulch from *Mucuna bracteata* and biofertilizer. It reduced NPK dosage during taro plant vegetative growth, aiming to provide recommendations for more effective and sustainable taro cultivation. This study aims to determine the effects of *Mucuna bracteata* organic mulch application and biofertilization on reducing the need for NPK fertilizer and on the vegetative growth of taro plants (*Colocasia esculenta* L.).

2. Materials and Methods

Time and Place

The research was conducted from May to August 2025 at the Experimental Garden of the Faculty of Agriculture, University of Riau, Bina Widya Campus KM 12.5, Bina Widya Village, Bina Widya District, Pekanbaru City. Analysis of the soil's physical, chemical, and biological properties was conducted at the Soil Science Laboratory, Faculty of Agriculture, University of Riau.

Research Preparation

The research preparation began with the rejuvenation and multiplication of the cellulolytic bacterial consortium (*Bacillus cereus* JP6, *Bacillus cereus* JP7, *Proteus mirabilis* TKKS3, *Proteus mirabilis* TKKS7, *Providensia vermicola SA1 and Bacillus cereus SA6*) in Nutrient Broth media. 0.4 g of NB medium was mixed with 40 mL of distilled water in an Erlenmeyer flask, then 1 loopful of the bacterial consortium was added, and the mixture was incubated for 1 × 24 hours at room temperature. The biofertilizer was prepared by mixing the consortium culture with 4 L of rice washing water, adding 400 g of melted brown sugar, and incubating for 2 weeks at room temperature, then applying it. The collection of organic mulch using *Mucuna bracteata* litter was carried out one week before application in the beds. The litter was collected and dried to the required total dose per bed. Soil sampling was carried out twice, namely before planting and after treatment was given at a depth of 0-20 cm using a soil sampler for analysis of physical

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properties (Bulk Density, Particle Density, and Total Pore Space), chemical (soil pH, Total N, Available P, Total K, Organic C), and soil biology (Total Plate Count).

Preparation of the research site included measuring a 160 m² plot measuring 16 m by 10 m. The land was cleared of undergrowth, trash, and all existing vegetation, then soil cultivation was carried out, and 20 research beds were created, measuring 3.5 m x 1.5 m with 50 cm of drainage between beds. Treatment labels were attached to each bed according to the research plan.

Seedling Planting

Planting is carried out by creating a spacing of 70 cm x 50 cm, then digging a planting hole 20 cm deep. Taro seeds are selected for an average size, then planted by burying the sprouted seeds in the planting hole and covering them with inceptisols soil.

Treatment Application

Mucuna bracteata organic mulch was applied to the bed surface one week after planting at the following doses: 3 kg m^{-2} (15.75 kg $beds^{-1}$) and 1.5 kg m^{-2} (7.88 kg $beds^{-1}$). Mutiara 16-16-16 NPK fertilizer was applied once in the afternoon, 14 days after planting, by sprinkling it in a circle at a distance of 10 cm from the plants, according to the treatment doses: 15 g $plant^{-1}$, 11.25 g $plant^{-1}$, and 7.5 g $plant^{-1}$. Biofertilizer was applied by pouring 10 mL from a measuring cup onto each plant at 14, 28, 42, and 56 days after planting.

Plant Maintenance

Watering is done twice a day, in the morning and evening, using a watering can or hose, until the soil is moist. If it has rained and the soil is still moist, watering is not necessary. Replanting is done 7 days after planting, replacing plants that are not growing or growing abnormally with interplants. Weed control is carried out mechanically around the beds and drainage to prevent competition for water, nutrients, and sunlight. Aphid pest control (Aphis gossypii) is carried out using a pesticide containing the active ingredient Deltamethrin 2.5% at a dose of 1 mL L^{-1} of water, starting 42 days after planting and continuing every 2 weeks until 84 days after planting.

Research Design

This research was conducted experimentally using a non-factorial Completely Randomized Design (CRD) with five treatment levels and four replications, yielding 20 experimental units. Each research bed consisted of 15 plants spaced 70 cm × 50 cm, resulting in a total population of 300. Three samples were taken from each bed in the center, resulting in 60 sample plants. The treatments applied consisted of P1, namely 100% NPK fertilizer (15 g $plant^{-1}$), P2, namely 75% NPK fertilizer (11.25 g $plant^{-1}$) + four times organic fertilizer application + 3 kg m^{-2} organic mulch *Mucuna bracteata*, P3, namely 75% NPK fertilizer (11.25 g $plant^{-1}$) + four times organic fertilizer application + 1.5 kg m^{-2} organic mulch *Mucuna bracteata*, P4, namely 50% NPK fertilizer (7.5 g $plant^{-1}$) + four times organic fertilizer application + 3 kg m^{-2} organic mulch *Mucuna bracteata*, and P5, namely 50% NPK fertilizer (7.5 g $plant^{-1}$) + four times organic fertilizer application + 1.5 kg m^{-2} organic mulch *Mucuna bracteata*.

Parameter Observation and Data Analysis

Observations were made on plant growth parameters. The parameters observed included the length of the leaf stalk measured using a meter from the base of the fifth leaf stalk attached to the stem to the point where it meets the leaf blade, the number of leaves per plant calculated on leaves that had grown and opened perfectly, the leaf area calculated on the fifth leaf blade using the formula Y = a P × L with the value of a determined according to three groups of P/L ratios, namely Y = 0.9462 P × L for a P/L ratio of less than 1.10, Y = 0.9109 P × L for a P/L ratio between 1.10–1.19, and Y = 0.8860 P × L for a P/L ratio of more than 1.20, the leaf area index calculated using the formula LAI = Leaf area (m²) / Land area (m²), the stem diameter measured using a

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vernier caliper at a height of 10 cm from the base of the stem, the chlorophyll content measured using a chlorophyll meter on the fifth leaf at the age of 91 days after planting, the soil temperature measured using a digital soil thermometer with inserting the tool into the soil, and soil moisture was measured using a soil moisture meter by inserting the tool into the soil to obtain a reading of the percentage of soil moisture. The data were analyzed using Analysis of Variance (ANOVA) in the Statistical Analysis System (SAS) version 9.00, followed by Duncan's New Multiple Range Test (DMRT) at the 5% level.

3. Results and Discussion

The results of the study showed that the combination of organic mulch (*Mucuna bracteata*), biofertilizer, and a reduced dosage of NPK fertilizer had a significant effect on the vegetative growth of taro plants and on the physical, chemical, and biological properties of the soil. In general, treatments P2, P3, and P4 provided a better growth response than P1, which only used 100% NPK fertilizer without mulch, indicating that a 25–50% reduction in inorganic fertilizer was still able to support plant growth if balanced with the addition of organic matter and the activity of soil microorganisms.

The results showed that integrating organic mulch (*Mucuna bracteata*), a biofertilizer based on cellulolytic bacteria, and reduced doses of NPK fertilizer can increase taro plant vegetative growth while improving soil physical, chemical, and biological properties. The effectiveness of mulch in reducing soil temperature and increasing humidity was clearly evident in treatments P2, P3, and P4, which resulted in higher stem length, leaf area, and leaf area index than the treatment without mulch.

This phenomenon is consistent with the findings of Zhang et al. (2023), which state that organic mulch effectively reduces soil temperature fluctuations and increases water retention, thereby creating more stable rooting conditions for plant growth. A moister, warmer rooting environment promotes cell elongation and meristem activity, as also explained by Gallart et al. (2021), as a general physiological response of plants to a soil environment maintained by organic mulch.

The relatively lower nitrogen (N) value observed in treatment P1, despite the application of 100% NPK fertilizer, may be attributed to the absence of organic matter in this treatment. Soils without organic inputs generally have a lower capacity to retain and stabilize nutrients, particularly nitrogen, which is highly mobile in the soil system. As a result, nitrogen derived from inorganic fertilizers is more susceptible to losses through leaching, especially in soils with high porosity or under conditions of high rainfall. Previous studies have reported that nitrate is the most mobile form of nitrogen and is easily leached from soil due to its negative charge, which prevents it from being retained by soil colloids.

Reducing the NPK fertilizer dose by 25–50% still results in good vegetative growth in taro when combined with biofertilizers. PGPR-based biofertilizers, particularly cellulolytic bacteria, are known to increase nitrogen mineralization and nutrient uptake efficiency, thereby maintaining optimal N uptake even when inorganic fertilizers are reduced.

This finding is in line with the report by Turan et al. (2024), which states that PGPR is able to increase nitrogen utilization and optimize vegetative growth. In addition, the integration of inorganic and organic fertilizers has been shown to increase fertilization efficiency and maintain crop yields, as confirmed by Chen et al. (2024), in a comprehensive assessment of intensive farming systems.

Changes in soil properties after treatment reflected improvements in soil quality, particularly in the mulch treatment. Bulk density decreased significantly in P3, P4, and P5, indicating that organic matter from mulch increased soil aggregation and porosity. This finding is consistent with a

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meta-analysis. Li et al. (2021) and Somasundaram et al. (2020) reported that organic mulch improved soil structure, water retention, and aeration. The decrease in bulk density was accompanied by an increase in total pore space, indicating that mulch directly improves soil physical conditions by adding organic matter.

Table 1. Analysis of soil physical properties

Soil Properties	Prior to Treatment	After Treatment				
		P1	P2	P3	P4	P5
Physics						
Bulk Density	1.37 (heavy)	1.18 (currently)	0.87 (light)	0.97 (currently)	0.76 (light)	0.79 (light)
Particle Density	3.38	1.89	1.87	1.92	1.87	1.9
Total Pore Space (%)	55.74 (Good)	44.73 (not good)	60.76 (Good)	52.85 (Good)	52.72 (Good)	60.63 (Good)
Chemistry						
pH (H_2O)	5.74 (sour)	6.38 (sour)	6.42 (sour)	6.63 (neutral)	6.38 (sour)	6.57 (sour)
C-Organic	2.24 (currently)	2.53 (currently)	2.95 (currently)	2.99 (currently)	3.39 (tall)	2.54 (currently)
N Total (%)	0.09 (low)	0.11 (low)	0.32 (currently)	0.53 (tall)	0.11 (low)	0.18 (low)
P Available P_2O_5 Olsen (ppm)	127.28 (very high)	147.78 (very high)	139.72 (very high)	155.65 (very high)	133.65 (very high)	132.30 (very high)
Total K_2O HCl 25% (mg $100g^{-1}$)	36.28 (currently)	41.82 (tall)	42.26 (tall)	39.98 (currently)	42.47 (tall)	39.93 (currently)
Biology						
Total Plate Count(TPC) (cfu g^{-1})	52 x 10^{12}	39x 10^{12}	83x 10^{11}	239 x 10^{12}	168 x 10^{12}	98 x 10^{12}

Chemically, the increase in soil pH towards neutrality in the mulch treatment indicates that the decomposition of organic matter releases base cations that can reduce soil acidity. This explanation is consistent with studies by Chatterjee et al. (2022), which show that organic mulch increases soil pH through the processes of humification and base accumulation. In addition, the increases in organic C and total nitrogen in treatments P3 and P4 are consistent with the findings of Lubbers et al. (2021), who found that organic inputs increase available mineral nitrogen and soil microbial biomass by increasing carbon pools.

Treatments P4 and P5 also showed a significant increase in soil microorganism populations (TPC), indicating that legume mulch such as *Mucuna bracteata* is a readily

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decomposable carbon source and can enhance microbial activity. Fagbola et al. (2019) reported similar results, in which legume mulch increased soil biological activity and improved organic decomposition.

Overall, empirical evidence from this study and recent international literature confirms that the combination of organic mulch and biofertilizer allows for reduced inorganic fertilizer doses without reducing vegetative growth. This integrated fertilization technology effectively improves soil fertility and supports a more efficient, environmentally friendly, and sustainable taro cultivation system.

Table 2. Observation parameters

Observation Parameters	Combination Treatment				
	P1	P2	P3	P4	P5
Leaf Stalk Length	55.30 b	71.07 a	69.12 ab	66.60 ab	60.87 ab
Number of Leaves	6.16 b	6.08 b	6.16 b	7.16 a	5.58 b
Leaf Area	0.05 b	0.08 a	0.08 a	0.09 a	0.07 ab
Leaf Area Index	0.81 b	0.83 b	1.42 a	0.99 b	1.00 b
Stem Diameter	47.14 a	52.71 a	53.47 a	49.04 a	51.56 a
Chlorophyll Content	62.80 ab	59.25 ab	70.07 a	55.22 b	66.12 a
Soil Temperature	30.62 a	27.95 b	28.22 b	27.10 b	28.37 b
Soil Moisture	32.50 d	62.50 a	41.25 c	56.25 b	41.25 c

Note: Numbers in the column followed by the same lowercase letters are not significantly different according to Duncan's test at the 5% level 100% NPK {Urea (15 g plant^{-1}), 75% NPK (11.25 g plant^{-1}), 50% NPK (7.5 g plant^{-1})}; biofertilizer 10 mL (applied 4 times); organic mulch *Mucuna bracteata* (3 kg m^{-2} and 1.5 kg m^{-2}).

Based on the results, the combination of NPK fertilizer, biofertilizer, and organic mulch (*Mucuna bracteata*) treatments elicited distinct responses in vegetative growth parameters of taro plants. In general, the combination of NPK reduction, biofertilizer application, and organic mulch application resulted in increased growth compared to treatment P1 (100% NPK). This indicates that reducing inorganic fertilizers can still support plant growth as long as it is supplemented with organic material and active soil microorganisms.

Applying 75% and 50% NPK fertilizers with *Mucuna bracteata* organic fertilizer and organic mulch can produce higher yields because the bacteria in the organic fertilizer can accumulate nutrients and other soil compounds. This is supported by the opinion of Kezia (2020), who argues that microorganisms in biofertilizers can help accumulate nutrients such as nitrogen and other compounds and dissolve phosphorus, enabling NPK fertilizers to be more effectively absorbed by plants. The main content of biofertilizers is a bacterial consortium comprising Bacillus cereus, Proteus mirabilis, and Providencia vermicola. These bacteria belong to the Plant Growth Promoting Rhizobacteria (PGPR) group (Jannah et al., 2022). The PGPR group of bacteria promotes plant growth by ensuring the availability of micro- and macronutrients, synthesizing various phytohormones, inducing stress resistance, and producing siderophores, antifungal compounds, and lytic enzymes (Hussain et al., 2015).

PGPR bacteria can support plant growth by providing nutrients for vegetative growth. According to the statement Situngkir et al. (2021), a biofertilizer containing PGPR microbes plays a role in increasing nutrient availability through mineralization, N fixation, and P dissolution, as well as

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producing phytohormones that can stimulate vegetative plant growth, including stems. Providencia vermicola bacteria can fix nitrogen, dissolve phosphate, and produce auxin (Hussain et al., 2015). Proteus mirabilis bacteria in biological fertilizers can synthesize abscisic acid (Kumar et al., 2022). This statement suggests that the consortium's biofertilizer can effectively mediate plant growth. Chaudhary et al. (2022) stated that biofertilizers can directly mediate vegetative plant growth by means of bacteria contained in biofertilizers that fix nitrogen, dissolve phosphate and micronutrients, and produce phytohormones.

The high total N and available P content in this study are shown in Appendix 3.3.2. The total N content met the high criteria at 0.53, and the available P content met the very high criteria at 155.65. The combination of treatments in this study resulted in high leaf stalk length, leaf blade length, and leaf area. These high values in this study indicate that taro leaves contain a large amount of chlorophyll, enabling effective photosynthesis, consistent with the statement. Adhikary et al. (2024) state that the leaves are wide and green, indicating that the chlorophyll they contain is abundant. Ramdani et al. (2024) state that in these conditions, sunlight in the form of protons absorbed by plants will increase to carry out photosynthesis activity in the light reaction, which will have an impact on increasing the rate of photosynthesis in plants, which will then be translocated to all plant organs, including influencing increased crop yields.

Leaf area index (LAI) is an important parameter in plant ecology. The leaf area index (LAI) of a plant is defined as the leaf area per unit of land area (Aji and Kusdiana, 2022). LAI can be an indicator of canopy health or development because it affects how light moves through the canopy. LAI is closely related to the shape and distribution of leaves in the canopy. Leaf canopy width increases at the beginning of plant growth and influences increases in LAI (Susanti and Safrina, 2021).

The leaf area index value was not optimal in the 100% NPK fertilizer treatment, according toAnna (2021), which can be caused by the loss of nutrients (especially nitrogen) due to leaching or washing and denitrification (loss of nitrogen due to conversion to gas). *Mucuna bracteata* litter, which is organic material, is well decomposed by microorganisms that develop from the applied biofertilizer. Tóth et al. (2023) stated that the large number of active microorganisms in biofertilizers supports the decomposition of organic materials in soil, thereby making nutrients more readily available for vegetative plant growth.

Increasing LAI will increase net assimilation rate (NAR), namely the ability of plants to produce dry matter through the assimilation process per unit of leaf area per unit of time (g/dm^2/week) (Zakariyya, 2016). Leaves play a very important role in plant photosynthesis and produce most of the biomass, so the number of leaves and LAI value will also affect plant yields (Kinhal, 2020). Aji and Kusdiana (2022) state that a value of 1 on LAI indicates that the number of leaves that can photosynthesize is around 50%.

Biofertilizers contain microorganisms that can mobilize nutrients from the soil and change them into forms that can be used. can be used through biological processes (Mazid and Khan, 2015). The biofertilizer used in this study contains Bacillus cereus, a PGPR that produces growth hormones that promote plant growth, especially in the stalk or stem. The large number of bacteria in biofertilizer can increase the availability of nutrients to plants. The bacteria in the biofertilizer can develop well, as seen from the results of soil biological analysis (Appendix 3.3.3), namely Total Plate Count (TPC), treatment of 75% NPK fertilizer + biofertilizer + 1.5 kg m^{-2} produced a bacterial count of 239 x 1012 cfu/g.

Microorganisms can reproduce well in a supportive environment. The results of the study showed that the soil pH,

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temperature, humidity, and physical structure of the soil from the treatment of 75% NPK fertilizer + biofertilizer + organic mulch *Mucuna bracteata*

1.5 kg m^{-2} were classified as good; this is shown in Appendix 3.3, namely the analysis of the soil's physical, chemical, and biological properties after planting. This is evident in one of the soil's chemical properties after treatment: a neutral pH of 6.63. At this soil pH, bacteria can grow well. This aligns with the study's results. Figiel et al. (2025), which states that pH 5.5 –7.2 is a pH with a balanced point that can optimally support microbial activity, including phosphate-solubilizing microorganisms, thus creating a priming effect, namely, microbial metabolites increasingly increase the availability of phosphorus and plant growth.

Increase in soil pH according to Sembiring et al. (2015) can occur due to the addition of organic mulch *Mucuna bracteata*, which can produce organic acids in the form of humic acid and fulvic acid produced during the decomposition process. Organic acids have a negative charge that can bind cations. The large number of microorganisms in the soil facilitates the decomposition of *Mucuna bracteata* mulch as organic soil material, ensuring that nutrients are quickly available to plants. This is in line with the results of research by Ali et al. (2024), which states that the provision of biofertilizer increases enzyme activity, microbial biomass, accelerates the decomposition of organic matter, and the rate of C and N mineralization, which is related to increasing the availability of N and P that plants can take up.

Increasing the dose of *Mucuna bracteata* organic mulch will increase the amount of protein and amino acids produced through decomposition. Sembiring et al. (2015) state that the protein and amino acids obtained from *Mucuna bracteata* organic mulch decompose into ammonium ($NH4^{+}$) and nitrate (NO3-), which are the major sources of N in the soil. Mulching helps balance soil temperature and humidity, thereby supporting the activity of enzymes and microbes that play a role in nutrient mineralization (Zhang et al., 2023).

Pou et al. (2021) state that the organic content of mulch can serve as an energy source for soil microbes activated by biofertilizers, thereby enhancing nutrient mineralization and supporting plant growth. The combination of organic mulch, biofertilizers, and reduced NPK doses not only helps control soil temperature but also supports sustainable soil fertility.

4. Limitations and Future Directions

This study has demonstrated robust results supported by statistical analysis. However, it has several limitations, including the following: First, this study found that a combination of treatments with a 50-75% reduction in NPK, combined with biofertilizer and *Mucuna bracteata* mulch, resulted in an increase in leaf stalk length of up to 71.07 cm in the P2 treatment compared to 55.30 cm in the control (P1), and an increase in leaf area of up to 0.08–0.09 cm compared to 0.05 cm. However, the effect of this combination on the generative phase and yield of taro plants has not been observed. Second, this study was conducted only at a single location, the University of Riau experimental garden. Therefore, the improvements in soil properties, such as a decrease in bulk density from 1.37 to 0.76 g cm^{-3} and an increase in soil porosity of more than 60% in the mulch treatment, cannot be confirmed in different agroecosystems, where different soil and climate conditions may exhibit different responses. Third, this study has not identified the specific contribution of each bacterium in the bacterial consortium within the biofertilizer (such as Bacillus cereus, Proteus mirabilis, and Providencia vermicola) to increasing nutrient availability, despite a significant increase in the soil microbial population (up to 239×10^{12} cfu g^{-1}). Fourth, the increase in organic carbon content to 3.39% and total

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nitrogen to 0.53%, indicating increased soil fertility, could not be directly measured. The dynamics of *Mucuna bracteata* mulch decomposition, in terms of nutrient release rates and its suitability to plant needs, could not be directly measured. Fifth, this study could not determine the minimum limit for inorganic fertilizer use that would still maintain optimal plant growth outside the 25-50% range. Sixth, understanding of plant physiological mechanisms such as photosynthesis rate, nutrient uptake efficiency, and enzyme activity remains unknown because it only measured chlorophyll content in taro leaves.

Some future research directions that need to be pursued include the following. First, further studies are needed to evaluate the combined effect of *Mucuna bracteata* mulch, biofertilizer, and NPK reduction on tuber yield, quality, and overall taro productivity. Second, further research is needed on reducing inorganic fertilizers, for example, up to 75% or even eliminating NPK fertilizers, to determine the optimal limits for chemical fertilizer use in an integrated system based on organic matter and microbes. Third, further research is needed on soil-bacteria-plant interactions to explain the relationship between increased bacterial populations and improved soil properties and their contribution to plant growth. Fourth, studies are needed on the decomposition kinetics of *Mucuna bracteata* mulch, including the rates of carbon and nitrogen mineralization, and the synchronization of nutrient release with plant needs, to determine the most efficient mulch dosage (e.g., 1.5 vs. 3 kg m^{-2}). Fifth, further research is needed into the effects of biofertilizers on taro plants cultivated in various soil types (Ultisol, Inceptisol, Andisol) and under various agro-ecosystem conditions. Sixth, evaluation of the stability and shelf life of bacteria as biofertilizers, along with economic and environmental impact analyses, is needed, such as production cost efficiency, reduced dependence on chemical fertilizers, increased soil organic carbon, and potential reductions in greenhouse gas emissions.

5. Conclusion

The combination of 75% and 50% NPK fertilizers with biofertilizer and *Mucuna bracteata* organic mulch produced vegetative growth comparable to that from 100% NPK fertilizer. These findings demonstrate that integrating organic materials and soil microorganisms can sustainably improve fertilization efficiency and soil quality.

Future research should evaluate the effects of this integrated technology on generative growth and tuber yield under different agroecosystem conditions. The limitation of this study is its focus on vegetative parameters; therefore, further studies are needed to develop comprehensive cultivation recommendations.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used ChatGPT to assist with language editing and manuscript structuring. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication.

Author Contributions Statement

The first author contributed to the development of the research concept, data analysis, interpretation of results, and manuscript writing and discussion. The second author contributed to determining the research theme, preparing the research design, and providing scientific input on the manuscript content. The third author contributed to field research, data collection, and documentation of research activities. All authors have read and approved the final version of the manuscript.

Declaration of Competing Interest

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.

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