

Optimizing banana corm-based local microorganisms for reduced NPK fertilization in pak choi (*Brassica rapa*)

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Abstract. Purba JH, Suarmika IGM, Prabawa PS. 2026. Optimizing banana corm-based local microorganisms for reduced NPK fertilization in pak choi (*Brassica rapa*). *Asian J Agric* 10 (1): g100145. <https://doi.org/10.13057/asianjagric/g100145>. This study evaluated the effectiveness of banana corm-based local microorganisms (MOL) in reducing inorganic NPK fertilizer, particularly nitrogen, phosphorus, and potassium, inputs while maintaining pak choi (*Brassica rapa*) productivity, as measured by fresh and oven-dry biomass. This study quantitatively evaluates MOL × NPK interactions and identifies the agronomic optimum MOL dose using regression analysis, a topic that has rarely been addressed in previous MOL studies. The experiment was conducted from December 2023 to February 2024 in a lowland tropical agroecosystem in Bali, Indonesia, using a factorial Randomized Complete Block Design with two factors: three MOL doses (0, 30, and 60 mL polybag⁻¹) and four NPK levels (100%, 75%, 50%, and 25% of the recommended dose). Growth and yield parameters included plant height, leaf number, leaf area, and fresh and oven-dry biomass of shoots, roots, and total plants. Analysis of variance showed that MOL application significantly affected leaf area, root biomass, and total biomass ($p < 0.05$), whereas NPK level alone was not significant. However, a significant MOL × NPK interaction was observed for root and total biomass ($p < 0.05$). The 30 mL MOL treatment combined with 50-75% NPK produced the highest biomass, indicating a synergistic effect and allowing up to a 50% reduction in inorganic NPK fertilizer without loss of productivity. Quadratic regression analysis identified an agronomic optimum MOL dose of approximately 33 mL polybag⁻¹ under reduced NPK conditions ($R^2 = 0.82$). This study provides quantitative evidence that integrating MOL with reduced NPK fertilization improves nutrient-use efficiency in pak choi cultivation. However, the results are based on a short-term pot experiment, and field-scale validation is required. The integration of locally available organic microbial inputs offers a promising approach to support more sustainable and cost-effective vegetable production systems.

Keywords: Banana-corm MOL, biofertilizer optimization, *Brassica rapa*, inorganic NPK fertilizer, yield response

INTRODUCTION

The intensification of vegetable production systems has been strongly associated with increased dependence on inorganic fertilizers, particularly nitrogen, phosphorus, and potassium (NPK), to achieve rapid biomass accumulation and high marketable yields. While these inputs have contributed substantially to productivity gains, their excessive and inefficient use has resulted in declining soil quality, reduced microbial diversity, nutrient imbalances, and environmental pollution through leaching and greenhouse gas emissions (Tiwari et al. 2023; Purba 2025; Nikmatullah et al. 2026). These challenges are especially pronounced in short-cycle leafy vegetables such as pak choi (*Brassica rapa*), which are commonly cultivated under high-input regimes in Southeast Asia to meet continuous market demand. Similar patterns of fertilizer overuse and associated environmental risks have been reported in intensive leafy vegetable systems worldwide, including in Asia, Europe, and peri-urban production areas in developing regions, highlighting the global relevance of sustainable nutrient management strategies (Wu et al. 2024).

Pak choi is a fast-growing leafy vegetable with high nutrient requirements over a short growth period, making it

particularly sensitive to fertilizer management strategies. Farmers often apply NPK fertilizers at or above recommended rates to avoid yield penalties, despite rising input costs and increasing awareness of environmental risks. Consequently, there is growing interest in alternative or complementary nutrient management approaches that can improve nutrient-use efficiency while reducing dependence on synthetic fertilizers (Rehman et al. 2022).

Biofertilizers and biostimulants have emerged as promising tools to address these challenges by enhancing nutrient availability, stimulating root development, and improving plant physiological performance (Muliarta and Purba 2020; Muttulani 2025; Setyaningrum et al. 2025). One such input is banana corm-based local microorganisms (MOL), a locally produced biofertilizer commonly derived from agricultural residues and fermented substrates (Anderson et al. 2019; Du et al. 2021). Banana corm-based MOL is of particular interest because banana corms are abundant agricultural by-products rich in potassium, carbohydrates, and naturally occurring beneficial microorganisms loss (Kumari et al. 2020). Previous studies have reported positive effects of banana corm MOL on vegetative growth and yield in several crops (Haruna et al. 2025; Amri et al. 2026). However, reported responses are often inconsistent across crops and application rates, and

most studies evaluate MOL in isolation without systematically examining its interaction with mineral fertilizers.

A key limitation of existing MOL research is the lack of factorial experimental designs that combine MOL with graded reductions in inorganic NPK fertilizer. As a result, it remains unclear to what extent MOL can compensate for reduced mineral inputs or whether synergistic effects occur under reduced fertilization levels. In addition, dose-response relationships for MOL are rarely quantified, and many studies rely solely on mean comparisons without regression-based optimization. These gaps limit the development of evidence-based recommendations for integrated nutrient management.

Therefore, the present study aimed to (i) quantify the growth and biomass response of pak choi to different doses of banana corm MOL, (ii) evaluate the interaction between MOL application and graded reductions in inorganic NPK fertilizer, and (iii) identify an agronomically optimal MOL dose capable of maintaining productivity under reduced NPK inputs. This study hypothesizes that banana corm-based local microorganisms (MOL) can reduce inorganic NPK fertilizer requirements in pak choi cultivation without compromising yield. The study examines the effects of varying MOL doses combined with reduced NPK levels on plant growth, biomass production, and nutrient-use efficiency. The novelty of this study lies in its quantitative assessment of MOL \times NPK interactions within a factorial framework and the determination of an optimum MOL dose using regression analysis, providing practical guidance for reducing inorganic fertilizer use without compromising yield. By addressing these gaps, this study contributes to the advancement of integrated nutrient management strategies for sustainable leafy vegetable production under intensive cultivation systems.

MATERIALS AND METHODS

Study site and experimental conditions

The experiment was conducted from December 2023 to February 2024 in Tanguwisia Village, Seririt Sub-district, Buleleng District, Bali Province, Indonesia (8°11'S, 114°56'E; ± 30 m a.s.l.). The site represents a lowland tropical agroecosystem with an average air temperature of approximately 27°C and relative humidity ranging from 70-85% during the experimental period. The growth medium consisted of field soil classified as sandy loam with moderate drainage. Before use, the soil was air-dried under shade, homogenized, and sieved to remove debris. A treatment receiving 100% of the locally recommended NPK dose was included as an agronomic reference to facilitate interpretation of fertilizer reduction effects under prevailing soil conditions.

Experimental design and treatments

The study employed a factorial Randomized Complete Block Design (RCBD) (Gomez and Gomez 1984) with two treatment factors and three replications. The first factor was banana corm-based local microorganisms (MOL) dose,

consisting of three levels: 0 mL polybag⁻¹ (M0), 30 mL polybag⁻¹ (M1), and 60 mL polybag⁻¹ (M2). The second factor was inorganic NPK fertilizer level, applied at four proportions of the recommended dose: 100% (P4), 75% (P1), 50% (P2), and 25% (P3). These reduction levels were selected to reflect realistic fertilizer management scenarios commonly practiced by pak choi farmers and to identify thresholds at which yield reduction may occur.

Each treatment combination was applied to one experimental unit, defined as a single polybag planted with one pak choi plant. A total of 12 treatment combinations \times 3 replications resulted in 36 experimental units. Each unit consisted of 11 polybags, giving a total of 396 plants. Data were collected from all plants within each experimental unit and averaged before statistical analysis.

Preparation and application of banana corm MOL

Banana corm MOL was prepared following a standard fermentation protocol from previous studies (Wulandari et al. 2009). Fresh banana corms were chopped into small pieces and mixed with brown sugar as a carbohydrate source and clean water in a sealed plastic container. The mixture was fermented anaerobically for 7-10 days at ambient temperature until a characteristic fermented odor developed, indicating active microbial growth. After fermentation, the liquid fraction was filtered to remove solid residues and stored in airtight containers at room temperature until application.

Prior to application, the macronutrient content of the banana corm MOL was analyzed in the laboratory. The MOL contained total nitrogen (N) of 0.21%, available phosphorus (P₂O₅) of 0.08%, and potassium (K₂O) of 0.34% (w/v), indicating its potential contribution as a supplementary nutrient source in addition to its biostimulant and microbial functions. MOL was applied once at the time of planting as a soil drench. The designated volume (0, 30, or 60 mL polybag⁻¹) was diluted in 250 mL of clean water and poured evenly onto the growth medium around the plant base.

Planting material and growth medium

Pak choi (*B. rapa*) seedlings were raised in seed trays using a mixture of soil, compost, and sand (2:1:1, v/v/v). Uniform seedlings were transplanted into polybags (30 cm diameter \times 25 cm height) filled with approximately 10 kg of growth medium prepared from field soil, composted manure, and sand in the same proportion. This medium provided sufficient aeration and baseline nutrient availability for leafy vegetable growth (Pontsho et al. 2024).

Inorganic fertilizer application

The recommended inorganic fertilizer rate for pak choi in the study area is 250 kg ha⁻¹ of NPK (16-16-16). This rate was converted to an equivalent amount per polybag and adjusted according to treatment levels as: 100%, 75%, 50%, and 25%. Fertilizer was applied in two equal splits: at transplanting stage and at two weeks after planting (WAP), following standard management practices for short-cycle leafy vegetables (Siyum et al. 2022).

Crop management

Plants were irrigated twice daily to maintain near-field capacity moisture conditions. Weeds were removed manually, and no chemical pesticides or additional fertilizers were applied during the experiment. Pest and disease incidence was minimal and controlled by removing affected leaves, ensuring that treatment effects were not confounded by biotic stress.

Data collection

Growth and yield observations were recorded at the harvesting stage (35 days after planting). Plant height (in cm) was measured from the stem base to the tip of the longest leaf. The number of fully expanded leaves was counted per plant. Leaf area (cm²) was measured using a leaf area meter. At harvest, plants were separated into shoots and roots. Fresh weights (g) were recorded immediately after harvest, and samples were oven-dried at 70°C until constant weight to determine oven-dry shoot weight, root biomass, and total dry biomass (Vessey 2003).

Statistical analysis

All data were analyzed using Analysis of Variance (ANOVA) appropriate for a factorial RCBD to test the main effects of MOL dose, NPK level, and their interaction. Prior to analysis, data were examined for normality and homogeneity of variance. When significant effects were detected, treatment means were compared using the Least Significant Difference (LSD) test at the 5% probability level. Quadratic regression analysis was used to describe the dose–response relationship between MOL application and total oven-dry biomass under reduced NPK conditions. Pearson’s correlation coefficients were calculated to assess relationships among growth and yield variables (Munir et al. 2016). All statistical analyses were performed using Statistical Tool for Agricultural Research (STAR), Ver. 2.0.1. No specific ethical approval or experimental permits were required for this study.

RESULTS AND DISCUSSION

Growth responses to banana corm MOL

Banana corm-based local microorganisms (MOL) application produced clear and statistically significant improvements in several growth parameters, including leaf area, root fresh weight, root biomass, and total oven-dry biomass ($p < 0.05$). In contrast, plant height and number of leaves were not significantly affected by either MOL dose, NPK level, or their interaction ($p > 0.05$), and therefore are not discussed further in detail, as biomass-related traits were more responsive indicators of treatment effects in this study. Analysis of Variance (ANOVA) for total biomass is presented in Table 1. The 30 mL polybag⁻¹ dose (M1) consistently outperformed both the control (M0) and the higher dose (M2) (Table 2). For example, leaf area increased by 30.4% from 369.6 cm² in M0 to 482.1 cm² in

M1. The performance of plants treated with banana corm MOL was better than that of plants without banana corm MOL application, as shown in Figure 1.

The superior performance of the 30 mL polybag⁻¹ MOL treatment suggests that banana corm MOL contributed to biomass accumulation through mechanisms related to nutrient supply and root development. Laboratory characterization showed that banana corm MOL contained 0.21% N, 0.08% P₂O₅, and 0.34% K₂O (w/v), indicating that MOL provided supplementary macronutrients in addition to its microbial functions. Although these nutrient concentrations are relatively low compared with inorganic fertilizers, their continuous availability in the rhizosphere may have supported early root growth and nutrient acquisition, particularly under reduced NPK inputs.

This expansion of photosynthetically active surface area suggests enhanced light interception capacity, which directly translates into higher biomass accumulation in leafy vegetables (Kelly and Runkle 2024). The effect is likely linked to phytohormones such as auxins, cytokinins, and gibberellins produced during MOL fermentation, which stimulate cell division and expansion. Jafar et al. (2023) reported similar results in leafy greens, where MOL improved canopy structure and chlorophyll density.

Previous studies have suggested that MOL may contain phytohormones such as auxins and cytokinins that stimulate plant growth (Zakria et al. 2026). However, in the present study, phytohormone content was not directly measured; therefore, any hormonal effects are inferred cautiously based on published literature rather than claimed as demonstrated mechanisms. The discussion thus emphasizes measured parameters and observable biomass responses rather than unquantified biochemical pathways.

The application of banana corm-based local microorganisms (MOL) significantly influenced several key growth and biomass parameters of pak choi, particularly leaf area, root biomass, and total biomass. Across these variables, the 30 mL polybag⁻¹ dose (M1) consistently produced superior outcomes compared with both the control (M0) and the higher MOL dose (M2). These results demonstrate that MOL effectiveness followed a clear non-linear dose–response pattern rather than a monotonic increase with application rate.

Table 1. Analysis of Variance (ANOVA) for total biomass

Source of Variation	df	SS	MS	F value	Pr(>F)	Remark
Block	2	1.9460	0.9730	0.43	0.6547	ns
MOL (M)	2	61.0438	30.5219	13.55	0.0001	**
NPK (P)	3	11.8006	3.9335	1.75	0.1870	ns
M × P	6	43.5232	7.2539	3.22	0.0201	*
Error	22	49.5682	2.2531			
Total	35	167.8818				

Note: df: Degrees of freedom, SS: Sum of squares, MS: Mean square, ns: Not significant, *: Significant at $p < 0.05$, **: Significant at $p < 0.01$



Figure 1. The performance of plants: A. Treated with banana corm MOL, B. Without banana corm MOL application

Table 2. Effect of banana corm MOL dosage on leaf area (cm²), fresh root weight (g), oven-dry root weight (g), and total biomass (g) of pak choi plants at harvest (30 days after transplanting)

Treatment	Leaf area (cm ²)	Fresh root weight (g)	Root biomass (g)	Total biomass (g)
M0	369.63 a	4.98 a	0.74 a	7.23 a
M1	482.12 b	7.40 b	1.09 b	10.41 b
M2	399.98 a	5.53 a	0.85 a	9.02 a
LSD 5%	72.94	1.24	0.20	1.53

Note: Each number followed by the same letter in the same column is not significantly different based on the Least Significant Difference (LSD) at the 5% level

The observed increase in leaf area under M1 treatment (30.4% relative to M0) is agronomically important, as leaf expansion directly enhances photosynthetic capacity in short-cycle leafy vegetables. Rather than attributing this response solely to generalized “growth stimulation,” the data suggest that MOL application improved biomass accumulation through coordinated enhancement of both above- and below-ground growth. This interpretation is supported by the strong correlations between leaf area, root biomass, and total biomass, indicating that MOL effects on canopy development were closely linked to improved root system performance (Hwang et al. 2021; Shukla et al. 2020; Tejnecký et al. 2025).

The lack of further improvement at the higher MOL dose (60 mL polybag⁻¹) suggests that excessive microbial input may have reduced growth efficiency. Similar responses have been reported in biofertilizer studies where high microbial populations temporarily immobilize nutrients or disrupt rhizosphere balance, particularly in confined rooting volumes such as polybags. Thus, the present findings highlight that MOL acts optimally within a specific dosage range and that over-application does not confer additional benefits.

Root biomass responded strongly to MOL application, with fresh root weight increasing from 4.98 g in M0 to 7.40 g in M1 and root biomass from 0.74 g to 1.09 g. This

indicates more efficient root system development, which in turn supports greater nutrient and water uptake. The observed increase in root biomass under M1 (approximately 47% higher than the control) indicates a substantial improvement in root system development, which likely enhanced soil-root contact and resource acquisition capacity. This interpretation is supported by the strong positive correlation between root biomass and total biomass ($r > 0.80$), suggesting that biofertilizer-induced modifications in root architecture were a primary driver of biomass accumulation in this study, rather than a secondary or generalized effect (Lumbantoruan et al. 2023). Interestingly, M2 (60 mL) did not further increase growth and, in some cases, reduced performance, indicating a non-linear dose–response relationship. This mirrors results in other short-cycle crops, where excessive microbial inoculants can cause nutrient immobilization or rhizosphere imbalances (Hardiman et al. 2016).

Roots fresh and biomass responded strongly to MOL application, with M1 increasing root dry biomass by approximately 47% relative to the control. This response is critical for interpreting overall yield performance, as correlation analysis revealed root biomass to be the variable most strongly associated with total biomass accumulation ($r > 0.80$). These results indicate that MOL-mediated yield responses were driven primarily by enhanced root development rather than by changes in shoot morphology alone (Cirillo et al. 2023; Mostafa et al. 2024).

From a physiological perspective, improved root biomass increases the effective soil-root contact area, which can enhance nutrient and water acquisition efficiency. While direct measurements of nutrient uptake were not conducted in this study, the consistent association between root biomass and total dry matter supports the conclusion that MOL improved nutrient-use efficiency rather than simply increasing nutrient availability in the soil. This distinction is important, as it avoids speculative claims about nutrient uptake and instead grounds interpretation in observed plant traits (Cusack et al. 2021; Holz et al. 2024; Navarro et al. 2025).

NPK rate effects and nutrient-use efficiency

The effect of NPK fertilizer dosage on plant height, leaf number, and leaf area of pak choi at harvest (30 days after transplanting) is presented in Table 3. As a main effect, NPK rate did not significantly influence most growth variables ($p > 0.05$). Plant height, leaf number, and leaf area remained relatively stable across NPK levels of 100%, 75%, 50%, and 25% of the recommended dose. Slight reductions were observed only at the lowest NPK rate. This suggests that pak choi nutrient demand was met even at 50% NPK under the study's compost-enriched growth medium, especially when MOL was present (Khan et al. 2009; Purba et al. 2018). The ability of pak choi to maintain stable growth across reduced NPK levels, particularly under MOL application, is consistent with previous findings in integrated nutrient management systems. Biofertilizers have been shown to enhance nutrient availability through microbial-mediated processes such as nutrient solubilization, mineralization, and stimulation of root growth, thereby improving plant nutrient acquisition under reduced mineral fertilizer inputs (Khan et al. 2009; Purba et al. 2018; Shukla et al. 2020; Cirillo et al. 2023). In the present study, the comparable or higher biomass observed at 50% NPK combined with MOL, relative to 100% NPK without MOL, suggests that MOL did not merely supplement nutrients but enhanced the efficiency of nutrient uptake from both soil and applied fertilizers. Similar synergistic effects between microbial inoculants and reduced NPK inputs have been reported in leafy and horticultural crops, where improved rhizosphere functioning allows partial substitution of inorganic fertilizers without yield penalty.

Although improved nutrient-use efficiency is suggested following MOL application, it was not directly measured in this study. The interpretation is therefore based on the ability of MOL-treated plants to maintain comparable biomass under reduced NPK inputs. This indicates a more efficient use of available nutrients, while avoiding conclusions beyond the measured data.

MOL × NPK interaction effects

Significant interactions between MOL and NPK were observed for root biomass and total oven-dry biomass ($p <$

0.05). The highest total biomass (12.58 g) was achieved with M1P2 (30 mL MOL + 50% NPK), whereas the lowest (6.50 g) occurred in M0P2 (0 mL MOL + 50% NPK) (Table 4). This suggests a synergistic effect where optimal MOL enhances the efficiency of a moderately reduced NPK dose. The combination of 30 mL MOL with 50-75% of the recommended NPK dose produced biomass yields comparable to, or higher than, the full NPK treatment without MOL. This response can be partly attributed to the additional N, P, and K supplied by the MOL itself, together with improved root biomass, which enhances nutrient acquisition from both organic and mineral sources. These results provide experimental evidence that inorganic NPK fertilizer can be reduced by up to 50% without compromising pak choi biomass production when integrated with banana corm MOL.

Such synergy is consistent with earlier reports in other vegetables, where biofertilizers improved mineral nutrient uptake, leading to higher yields at reduced fertilizer rates. In our case, M1P1 provided both biological and mineral nutrient supply in a balance favorable for short-cycle leafy vegetable growth (Roeswitawati 2019; Bindu et al. 2025; Amri et al. 2026).

The significant interaction between MOL and NPK for total oven-dry biomass provides the strongest evidence for functional integration between biological and mineral nutrient inputs. The highest biomass was recorded under the M1P2 treatment (30 mL MOL + 50% NPK), whereas the lowest biomass occurred under reduced NPK without MOL. This contrast demonstrates that MOL did not simply replace mineral nutrients but modified the plant response to them.

Previous interpretations describing M1P1 or M1P2 as providing a “balanced” nutrient supply risk circular reasoning unless grounded in measurable outcomes. In this study, balance is operationally defined by superior biomass accumulation at reduced NPK input, supported by statistically significant interaction effects. The data therefore justify the conclusion that MOL improved the efficiency with which plants utilized available mineral nutrients, rather than asserting balance as an abstract concept.

Table 3. The effect of NPK fertilizer dosage on plant height, leaf number, and leaf area of pak choi at harvest (30 days after transplanting)

Treatment	Plant height (cm)	Leaf number (leaves)	Leaf area (cm ²)
P1	17.07 a	11.30 a	361.19 a
P2	17.88 a	11.67 a	446.45 a
P3	19.02 a	11.74 a	462.00 a
P4	18.32 a	11.63 a	399.32 a
LSD 5%	ns	ns	ns

Note: Each number followed by the same letter in the same column is not significantly different based on the Least Significant Difference (LSD) at the 5% level

Table 4. Differences in total biomass (g) of pak choi plants resulting from the application of banana corm MOL at each NPK fertilizer dosage level at harvest (30 days after transplanting)

Treatment NPK dosage	MOL dosage		
	M0	M1	M2
P1	6.84 ab	7.93 abcd	9.06 bcde
P2	6.50 a	12.58 g	8.85 abcde
P3	8.44 abcd	11.73 fg	7.95 abcd
P4	7.13 abc	9.40 cdef	10.23 defg
LSD 5%	2.54		

Note: Each number followed by the same letter is not significantly different based on the Least Significant Difference (LSD) at the 5% level

Mechanistically, this synergy is most plausibly explained by MOL-induced improvements in rhizosphere functioning, including enhanced microbial activity, organic acid production, and root growth stimulation. These processes can increase nutrient accessibility and uptake efficiency without necessarily increasing total nutrient pools. While direct microbial or soil chemical measurements were beyond the scope of this study, the consistent root-centered responses observed here align with established mechanisms reported in integrated nutrient management literature (Hiremath et al. 2024; Tejnecký et al. 2025).

The significant MOL \times NPK interaction observed in this study suggests that the effect of MOL is highly dependent on the availability of mineral nutrients, indicating a functional complementarity rather than a simple additive response. Under moderate NPK levels (50-75%), MOL application likely enhanced rhizosphere processes such as microbial activity, nutrient mineralization, and root-induced changes in soil chemistry, which together improved nutrient accessibility and uptake efficiency. This is consistent with reports that microbial inoculants can increase the efficiency of applied fertilizers by facilitating nutrient solubilization and stimulating root growth, particularly under suboptimal nutrient supply (Shukla et al. 2020; Cirillo et al. 2023). Conversely, under very low or very high input conditions, the benefits of microbial inputs may be constrained either by nutrient limitation or by microbial competition and temporary nutrient immobilization. Therefore, the superior performance of the M1P2 and M1P1 treatments reflects an optimal balance in which biological and mineral nutrient sources interact synergistically to maximize plant growth, rather than acting independently.

Dose-response optimization and agronomic implications

Quadratic regression analysis under 75% NPK (P1) indicated an agronomic optimum MOL dose of ~ 33.6 mL polybag $^{-1}$ ($R^2 = 0.816$) (Figure 2). Beyond this level, biomass declined, likely due to temporary nutrient immobilization or metabolic imbalances from high microbial populations. Such diminishing returns highlight the importance of dosage precision in biofertilizer application. This optimum closely matches effective MOL ranges reported in other crops, suggesting cross-crop applicability and simplifying farmer recommendations (Cazetta et al. 2007).

Quadratic regression analysis further reinforces the importance of dosage optimization. The estimated agronomic optimum of approximately 33.6 mL MOL polybag $^{-1}$ under reduced NPK conditions closely matches the empirically observed superiority of the 30 mL treatment. This convergence between statistical modeling and observed treatment performance strengthens confidence in the robustness of the recommendation.

Crucially, claims regarding fertilizer reduction are supported directly by quantitative treatment comparisons. The ability to reduce NPK application by up to 50% without yield loss is not inferred but demonstrated through statistically equivalent or superior biomass production

under MOL-integrated treatments. This distinction addresses concerns regarding speculative economic or agronomic benefits (Shukla et al. 2020; Mostafa et al. 2024).

Trait correlations and biomass drivers

Correlation analysis presented in Table 5 revealed that total biomass was most strongly associated with root biomass ($r = 0.90$, $p < 0.01$) and root fresh weight ($r = 0.88$, $p < 0.01$). Leaf area also correlated strongly ($r = 0.81$, $p < 0.01$), underscoring its role in productivity. Leaf number showed only a weak, non-significant correlation ($r \approx 0.35$), indicating that leaf expansion contributes more to yield than leaf count.

This pattern is consistent with previous studies in leafy vegetables, where leaf area has been identified as a more important determinant of yield than leaf number due to its direct influence on light interception and photosynthetic capacity (Shukla et al. 2020; Hwang et al. 2021; Talabany and Albarzinji 2023). In addition, the strong association between root biomass and total biomass observed in this study aligns with broader evidence highlighting the critical role of below-ground traits in enhancing water and nutrient acquisition, thereby supporting rapid shoot growth and biomass accumulation in short-cycle crops (Cusack et al. 2021; Cirillo et al. 2023; Talabany and Albarzinji 2023; Holz et al. 2024).

Comparative treatment performance

Across treatments, three performance patterns emerged. First, MOL improved growth and yield regardless of NPK level. Second, moderate NPK reductions (50-75%) with MOL achieved yields comparable to or better than full NPK without MOL. Third, very high MOL doses (M2) could reduce performance, particularly when paired with low NPK.

The superiority of M1P1 reflects the optimal nutrient synergy: MOL enhances nutrient mobilization and uptake, while 75% NPK ensures a steady mineral nutrient supply during rapid vegetative growth. This outcome aligns with principles advocating integrated nutrient management for sustainable intensification (Aasfar et al. 2021).

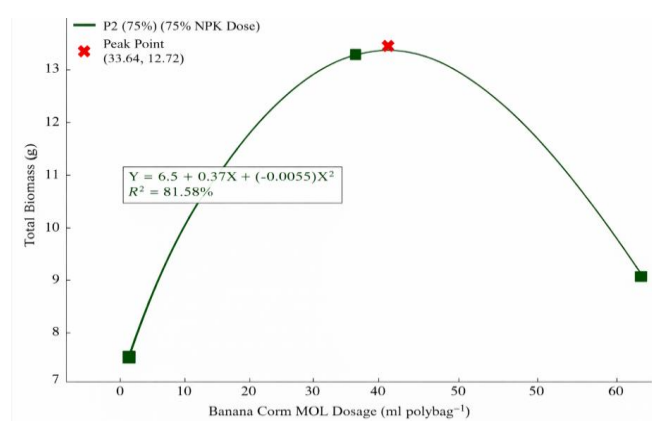


Figure 2. Quadratic regression curve showing the relationship between MOL dose and total biomass at 75% NPK

Table 5. Pearson's correlation coefficients between growth and yield parameters

	RDW	TDW	PH	LN	LA	SFW	SDW	RFW	TFW
RDW	1	0.8175	0.6238	0.3529	0.6424	0.6894	0.694	0.7713	0.5558
TDW	0.8175	1	0.6358	0.4889	0.7471	0.8135	0.8549	0.8396	0.7346
PH	0.6238	0.6358	1	0.551	0.7256	0.6426	0.7342	0.6452	0.6011
LN	0.3529	0.4889	0.551	1	0.5409	0.5531	0.5162	0.4117	0.5631
LA	0.6424	0.7471	0.7256	0.5409	1	0.8389	0.799	0.8204	0.5253
SDW	0.6894	0.8135	0.6426	0.5531	0.8389	1	0.8434	0.8154	0.638
SDW	0.694	0.8549	0.7342	0.5162	0.799	0.8434	1	0.8859	0.7411
RFW	0.7713	0.8396	0.6452	0.4117	0.8204	0.8154	0.8859	1	0.6281
TFW	0.5558	0.7346	0.6011	0.5631	0.5253	0.638	0.7411	0.6281	1

Note: RDW: Root biomass, TDW: Total Dry Weight, PH: Plant Height, LN: Leaves Number, LA: Leaves Area, SFW: Shoot Fresh Weight, SDW: Shoot biomass, SFW: Shoot Fresh Weight, TFW: Total Fresh Weight

Broader agronomic and economic implications

From an agronomic perspective, the demonstrated potential to reduce NPK by at least 50% without yield loss represents a significant step toward more sustainable pak choi production systems. Environmentally, reducing synthetic fertilizer use lowers the risk of nutrient leaching and eutrophication, issues often linked to high-input vegetable farming (Kathirvel et al. 2025). Economically, such reductions can substantially decrease production costs for smallholders, especially when paired with low-cost, locally produced MOL (Quoreshi et al. 2019).

The use of banana corms, an agricultural by-product, aligns with circular economy principles by converting waste into value-added inputs, as advocated in sustainable farming frameworks (Acevedo et al. 2021). The practical recommendation emerging from these results is the use of ~30 mL MOL per planting unit with 50-75% of recommended NPK, subject to local adaptation.

Implications for sustainable pak choi production

The evidence from this study suggests that banana corm MOL, when applied at optimal rates, can serve as an effective biostimulant to improve nutrient-use efficiency in pak choi production. This enables farmers to reduce NPK application rates by up to 50% without compromising yield, thereby lowering production costs and minimizing environmental risks associated with fertilizer overuse. The adoption of MOL also supports circular economy principles by transforming agricultural waste (banana corms) into a value-added input.

Limitations and future research directions

While the present study provides clear evidence of the agronomic benefits and optimum dosing of banana corm MOL under controlled conditions, further investigation is warranted to expand its applicability. Field-scale trials across diverse soil types and climatic conditions are needed to validate and refine dosage recommendations for broader farmer adoption.

Long-term studies should assess the cumulative effects of MOL use on soil health, microbial diversity, and nutrient cycling. Understanding the biochemical and microbiological mechanisms underlying MOL's interaction with mineral fertilizers would strengthen its theoretical

foundation and inform tailored formulations. Additionally, integrating the MOL application with other sustainable practices, such as organic mulching, crop rotation, and precision irrigation, may yield synergistic benefits for yield stability and environmental performance.

Economic analyses evaluating cost-benefit ratios and return on investment under real-world farm conditions would further support policy and extension efforts. Finally, exploring the potential of MOL in other high-value short-cycle crops could diversify its impact and enhance adoption in smallholder horticultural systems.

In conclusion, this study demonstrates that banana corm-based local microorganisms (MOL) can substantially reduce the requirement for inorganic NPK fertilizer while maintaining or improving pak choi (*B. rapa*) growth and yield. Across treatments, the application of 30 mL MOL plant⁻¹ combined with 50-75% of the recommended NPK rate produced fresh and dry biomass that was comparable to or higher than 100% NPK without MOL. Regression analysis revealed a strong quadratic relationship between MOL dose and total dry biomass ($R^2 = 0.82$), with the optimal response occurring at approximately 30 mL MOL plant⁻¹, indicating improved nutrient-use efficiency under reduced inorganic fertilizer inputs. These results demonstrate that integrating banana corm MOL with reduced inorganic fertilization can maintain pak choi biomass production while lowering fertilizer inputs by up to 50%. This approach offers a practical and environmentally friendly nutrient management strategy for intensive leafy vegetable production systems, particularly where fertilizer efficiency and cost reduction are priority concerns.

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REFERENCES

- Aasfar A, Bargaz A, Yaakoubi K, Hilali A, Bennis I, Zeroual Y, Meftah Kadmiri I. 2021. Nitrogen fixing *Azotobacter* species as potential soil biological enhancers for crop nutrition and yield stability. *Front Microbiol* 12: 628379. <https://doi.org/10.3389/fmicb.2021.628379>.
- Acevedo SA, Carrillo AJD, Flórez-López E, Grande-Tovar CD. 2021. Recovery of banana waste-loss from production and processing: A contribution to a circular economy. *Molecules* 26 (17): 5282. <https://doi.org/10.3390/molecules26175282>.
- Amri MR, Haris A, Saida S. 2026. Effects of different rates of maggot-based fertilizer and banana corm liquid organic fertilizer on the growth and yield of green mustard (*Brassica juncea* L.). *Agrogenesis J Sustain Agric Innov* 1 (2): 158-168. <https://doi.org/10.33096/agrogenesis.v1i2.775>.
- Anderson NT, Underwood JP, Rahman MM, Robson A, Walsh KB. 2019. Estimation of fruit load in mango orchards: Tree sampling considerations and use of machine vision and satellite imagery. *Precis Agric* 20 (4): 823-839. <https://doi.org/10.1007/s11119-018-9614-1>.
- Bindu SH, Prasanth P, Mamatha A, Kumar SP. 2025. Influence of inorganic nutrients and biofertilizers on growth parameters of palak. *Agric Assoc Textile Chem Crit Rev* 13 (4): 196-200. <https://doi.org/10.21276/AATCCReview.2025.13.04.196>.
- Cazetta ML, Celligoi MAPC, Buzato JB, Scarmino IS. 2007. Fermentation of molasses by *Zymomonas mobilis*: Effects of temperature and sugar concentration on ethanol production. *Bioresource Technol* 98 (15): 2824-2828. <https://doi.org/10.1016/j.biortech.2006.08.026>.
- Cirillo V, Romano I, Woo SL, Di Stasio E, Lombardi N, Comite E, Pepe O, Ventorino V, Maggio A. 2023. Inoculation with a microbial consortium increases soil microbial diversity and improves agronomic traits of tomato under water and nitrogen deficiency. *Front Plant Sci* 14: 1304627. <https://doi.org/10.3389/fpls.2023.1304627>.
- Cusack DF, Addo-Danso SD, Agee EA et al. 2021. Tradeoffs and synergies in tropical forest root traits and dynamics for nutrient and water acquisition: Field and modeling advances. *Front For Glob Change* 4: 704469. <https://doi.org/10.3389/ffgc.2021.704469>.
- Du C, Zhang L, Ma X, Lou X, Shan Y, Li H, Zhou R. 2021. A cotton high-efficiency water-fertilizer control system using wireless sensor network for precision agriculture. *Processes* 9 (10): 1693. <https://doi.org/10.3390/pr9101693>.
- Gomez KA, Gomez AA. 1984. *Statistical Procedures For Agriculture Research*. 2nd Edition. Jhon Wiley and Sons, New York.
- Hardiman BS, Gough CM, Butnor JR, Bohrer G, Detto M, Curtis PS. 2016. Coupling fine-scale root and canopy structure using ground-based remote sensing. *Preprints* 2016: 2016100088. <https://doi.org/10.20944/preprints201610.0088.v1>.
- Haruna N, Mudaffar RA, Kesia K, Ilyas Mattola P, Rosnina R. 2025. Upaya peningkatan hasil panen tanaman brokoli (*Brassica oleracea* L.) dengan pemberian mikroorganisme lokal (MOL) kulit pisang. *Perbal: Jurnal Pertanian Berkelanjutan* 13 (2): 197-206. <https://doi.org/10.30605/perbal.v13i2.6217>. [Indonesian]
- Hiremath SS, Prasanna NL, Sudhakar S, Arvind M, Akshaya CK, Nigam R, Kumar S, Elangovan M. 2024. A review on role of root exudates in shaping plant-microbe-pathogen interactions. *J Adv Microbiol* 24 (12): 1-17. <https://doi.org/10.9734/jamb/2024/v24i12868>.
- Holz M, Zarebanadkouki M, Benard P, Hoffmann M, Dubbert M. 2024. Root and rhizosphere traits for enhanced water and nutrients uptake efficiency in dynamic environments. *Front Plant Sci* 15: 1383373. <https://doi.org/10.3389/fpls.2024.1383373>.
- Hwang HH, Chien PR, Huang FC, Hung SH, Kuo CH, Deng WL, Chiang EPI, Huang CC. 2021. A plant endophytic bacterium, *Burkholderia seminalis* strain 869T2, promotes plant growth in *Arabidopsis*, pak choy, Chinese amaranth, lettuces, and other vegetables. *Microorganisms* 9 (8): 1703. <https://doi.org/10.3390/microorganisms9081703>.
- Jafar J, Syam A, Kasmira K. 2023. Pertumbuhan tanaman kangkung darat dengan pemberian mikroorganisme lokal (MOL) gamal (*Gliricidia sepium*) dan limbah ampas kelapa. *Jurnal Galung Tropika* 12 (3): 392-399. <https://doi.org/10.31850/jgt.v12i3.1045>. [Indonesian]
- Kathirvel L, Raviraj A, Arunadevi K, Kannan P, Gomathi V, Anandhi V. 2025. Sustained release fertilizers: A pathway to increased crop yield and efficient nutrient utilization - A review. *Plant Sci Today* 12 (sp1): 1-18. <https://doi.org/10.14719/pst.8148>.
- Kelly N, Runkle ES. 2024. Dependence of far-red light on red and green light at increasing growth of lettuce. *PLoS One* 19 (11): e0313084. <https://doi.org/10.1371/journal.pone.0313084>.
- Khan W, Rayirath UP, Subramanian S, Jithesh MN, Rayorath P, Hodges DM, Critchley AT, Craigie JS, Norrie J, Prithiviraj B. 2009. Seaweed extracts as biostimulants of plant growth and development. *J Plant Growth Regul* 28 (4): 386-399. <https://doi.org/10.1007/s00344-009-9103-x>.
- Kumari R, Kundu M, Das A, Rakshit R, Sahay S, Sengupta S, Ahmad MF. 2020. Long-term integrated nutrient management improves carbon stock and fruit yield in a subtropical mango (*Mangifera indica* L.) orchard. *J Soil Sci Plant Nutr* 20 (2): 725-737. <https://doi.org/10.1007/s42729-019-00160-6>.
- Lumbantoruan SM, Paulina M, Siaga E, Aggraini S, Febrianti. 2023. Growth response and nutrition uptake of corn plants on drought stress in peat soil. *IOP Conf Ser Earth Environ Sci* 1160 (1): 012020. <https://doi.org/10.1088/1755-1315/1160/1/012020>.
- Mostafa SSM, El-Hassanin AS, Soliman AS, El-Chaghaby GA, Rashad S, Elgaml NMM, Awad AA. 2024. Phytoremediation of potato industry wastewater for nutrient recovery, pollution reduction, and biofertilizer production for greenhouse cultivation of lettuce and celery in sandy soils. *Intl J Plant Biol* 15 (3): 652-672. <https://doi.org/10.3390/ijpb15030048>.
- Muliarta IN, Purba JH. 2020. Potential of loss of organic fertilizer in lowland rice farming in Klungkung District, Bali. *Agro Bali: Agric J* 3 (2): 179-185. <https://doi.org/10.37637/ab.v3i2.567>.
- Munir MA, Ahmad M, Ali MI, Mahmood Z, Afzal M, Sharif MN, Aslam M. 2016. Correlation and regression analysis of morphological traits in *Rumex dentatus*. *Bull Biol Allied Sci Res* 2016 (1): 2. <https://doi.org/10.54112/bbasr.v2016i1.2>.
- Muttulani MAJ. 2025. Enhancing hydroponic leaf lettuce (*Lactuca sativa*) production through optimized nutrient formulations. *Asian J Agric* 9 (2): 415-422. <https://doi.org/10.13057/asianjagric/g090208>.
- Navarro BB, Machado MJ, Figueira A. 2025. Nitrogen use efficiency in agriculture: Integrating biotechnology, microbiology, and novel delivery systems for sustainable agriculture. *Plants* 14 (19): 2974. <https://doi.org/10.3390/plants14192974>.
- Nikmatullah A, Sarjan M, Jihadi A, Nairfana I, Prasedya ES. 2026. Fertilization strategies alter growth and rhizosphere microbiome diversity in white potato (*Solanum tuberosum*). *Biodiversitas* 27 (1): d270135. <https://doi.org/10.13057/biodiv/d270135>.
- Pontsho T, Clement M, Yvonne M, Maboko M. 2024. Responses of different growing media ratios growth performance of spinach (*Spinacia oleracea* L.) under greenhouse conditions. *Res Crop* 25: 97-103. <https://doi.org/10.31830/2348-7542.2024.roc-1015>.
- Purba JH, Parmila IP, Sari KK. 2018. Pengaruh pupuk kandang sapi dan jarak tanam terhadap pertumbuhan dan hasil kedelai (*Glycine max* L. Merrill) varietas edamame. *Agro Bali: Agric J* 1 (2): 69-81. <https://doi.org/10.37637/ab.v1i2.308>. [Indonesian]
- Purba JH. 2025. Unsur hara makro. In: Ansar M (eds.). *Nutrisi Tanaman dan Pemupukan*. Azzia Karya Bersama, Padang. [Indonesian]
- Quoreshi A, Suleiman MK, Manuvel AJ, Sivadasan MT, Jacob S, Thomas R. 2019. Biofertilizers for agriculture and reclamation of disturbed lands: An eco-friendly resource for plant nutrition. *J Mech Contin Math Sci* spl1 (4): 231-243. <https://doi.org/10.26782/jmcs.spl.4/2019.11.00023>.
- Rehman IU, Islam T, Wani AH, Rashid I, Sheergojri IA, Bandh MM, Rehman S. 2022. Biofertilizers: The role in sustainable agriculture. In: Bandh SA (eds.). *Sustainable Agriculture*. Springer, Cham. https://doi.org/10.1007/978-3-030-83066-3_2.
- Roeswitawati D. 2019. Dosage and frequency test of liquid organic fertilizer banana hump to results and growth of cauliflower (*Brassica oleracea* L.). *Intl J Eng Technol* 8 (1.9): 656-660. <https://doi.org/10.14419/ijet.v8i1.9.30083>.
- Setyaningrum D, Suhita CP, Paryanto E, Ningsih H, Arifin Z, Suryadi D, Suprihatin DN, Nurhidayati F, Pradana AGR, Hantari D. 2025. Effect of organic fertilizer types and dosage on yield and nutrient uptake of red ginger in an Alfisol. *Asian J Agric* 9 (2): 636-644. <https://doi.org/10.13057/asianjagric/g090231>.
- Shukla SK, Sharma L, Jaiswal VP, Pathak AD, Tiwari R, Awasthi SK, Gaur A. 2020. Soil quality parameters vis-a-vis growth and yield attributes of sugarcane as influenced by integration of microbial consortium with NPK fertilizers. *Sci Rep* 10 (1): 19180. <https://doi.org/10.1038/s41598-020-75829-5>.
- Siyum N, Getu D, Purba JH, Bahta M. 2022. Enhancing faba bean production through promoting integrated faba bean gall management

- practices in Eastern Amhara Region of Ethiopia. *Agro Bali: Agric J* 5 (2): 369-375. <https://doi.org/10.37637/ab.v5i2.898>.
- Talabany NK, Albarzinji IM. 2023. Effects of salicylic acid on some growth and physiological characteristics of lettuce (*Lactuca sativa* L.) under cadmium stress conditions. *Sci J Univ Zakho* 11 (1): 37-44. <https://doi.org/10.25271/sjuoz.2023.11.1.987>.
- Tejnecký V, Luláková P, Šantrůčková H, Křížová P, Lehejček J, Hájek T, Mercl F, Bárta J, Němeček K, Drábek O. 2025. Arctic willow (*Salix polaris*) exudation as a driver of microbial activity and soil formation in the high arctic tundra. *Biogeochemistry* 168 (2): 30. <https://doi.org/10.1007/s10533-025-01222-x>.
- Tiwari AK, Moond V, Choudhari RJ, Badekhan A, Tejasree P, Baral K, Bharti R. 2023. Optimizing bio-fertilizers to address food security and advance nutritional sustainability. *J Exp Agric Intl* 45 (12): 235-249. <https://doi.org/10.9734/jeai/2023/v45i122284>.
- Vessey JK. 2003. Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil* 255: 571–586. <https://doi.org/10.1023/A:1026037216893>.
- Wu G, Liu B, Zhao M, Liu L, Wei S, Yuan M, Wang J, Chen X, Wang X, Sun Y. 2024. Integrated soil-crop system management promotes sustainability of intensive vegetable production in plastic shed systems: A case study in the Yangtze River Basin, China. *Agronomy* 14 (4): 807. <https://doi.org/10.3390/agronomy14040807>.
- Wulandari D, Fatmawati DN, Qolbaini EN, Praptinasari S. 2009. Penerapan MOL (Mikro-organisme Lokal) Bonggol Pisang sebagai Biostarter Pembuatan Kompos. [PKM-P]. Universitas Sebelas Maret, Surakarta. [Indonesian]
- Zakria MI, Soomro AA, Mahmooda Buriro, Jatoi WA, Shahzad H, Parveen H, Kaleri AA, Gul R. 2026. Effect of foliar applied Moringa (*Moringa oleifera* Lam.) leaf extract on growth, development and yield of mungbean (*Vigna radiata* L.). *Indus J Biosci Res* 4 (2): 58-76. <https://doi.org/10.70749/ijbr.v4i2.2900>.