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DIVERGENCE BETWEEN NUTRIENT ENRICHMENT AND AGRONOMIC RESPONSE OF MELON UNDER PUMAKKAL-ACTIVATED COTAYAM COMPOST

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A B S T R A C T

The development of microbially activated organic fertilizer is an important strategy for improving horticultural productivity while utilizing locally available organic waste. This study aimed to analyze the divergence between compost nutrient enrichment and the agronomic response of melon (*Cucumis melo* L.) to Cotayam compost fermented with different Pumakkal isolate formulations. Cotayam compost was prepared from cocopeat, shrimp-pond sediment, and chicken manure, and fermented under six treatments: P0 without isolates; P1 with three isolates; P2 with six isolates; P3 with nine isolates; P4 with twelve isolates; and P5 with fifteen Pumakkal isolates. The experiment employed a completely randomized design with six replications. The observed parameters included moisture content, total N, P_2O_5, K_2O, plant height, stem diameter, branch number, flowering time, fruit weight, and fruit sweetness. The results showed that increasing the number of Pumakkal isolates enriched compost nutrient content, with the highest values recorded in P5: 2.462% total N, 1.870% P_2O_5, and 2.237% K_2O. However, the most favorable agronomic response was observed in P3 rather than P5. P3 produced the highest plant height of 167.10 cm, the largest stem diameter of 12.83 mm, the earliest flowering at 13.67 days, the highest fruit weight of 1093.17 g, and high fruit sweetness of 15.40 °Brix. These findings indicate that the effectiveness of Pumakkal-activated Cotayam compost is not determined solely by the highest nutrient concentration but is likely related to how compost-derived nutrients meet crop physiological demands during growth and fruit development. Therefore, the nine-isolate formulation represents the most promising treatment for supporting melon production using locally sourced Cotayam compost.

INTRODUCTION

Melon (*Cucumis melo* L.) is a high-value horticultural crop whose productivity and fruit quality are strongly influenced by nutrient management during both vegetative and generative growth. This crop requires a balanced nutrient supply to support canopy formation, root development, flowering, fruit enlargement, and the accumulation of soluble solids that determine harvest quality. In intensive cultivation practices, these nutrient requirements are commonly fulfilled through synthetic fertilizers because they are readily available and relatively easy to apply. However, long-term dependence on mineral fertilizers has increasingly been criticized because it may lead to soil degradation, declining soil functional quality, and water pollution when intensive fertilizer inputs are not balanced with sufficient organic matter restoration (Latini et al., 2021). Therefore, developing fertilization systems that maintain productivity while improving soil quality is essential for sustainable melon cultivation.

One widely developed approach is the use of compost and organic amendments as part of circular nutrient management. Composting converts biodegradable residues into soil amendments rich in organic matter, reducing dependence on synthetic fertilizers. This strategy is not only related to nutrient supply but also to the restoration of soil structure, improvement of soil organic matter, and strengthening of soil biological activity. (Manea et al., 2024; Paradelo et al., 2023). In addition, using organic waste through composting can reduce environmental burdens associated with waste disposal, including potential emissions from unmanaged biodegradable materials. (Bruni et al., 2020; Kaushik et al., 2025). Thus, locally sourced compost is a strategic alternative fertilizer input in intensive horticultural systems, including melon cultivation.

Nevertheless, the use of compost as a nutrient source for crops presents specific agronomic challenges. Unlike synthetic fertilizers, which generally have more uniform nutrient composition and faster nutrient availability, organic fertilizers have more variable nutrient contents, and their nutrient release depends on microbial decomposition, compost maturity, environmental conditions, and the characteristics of the raw materials. In melon, which requires timely nutrient supply during rapid vegetative growth and fruit formation, a mismatch between nutrient release and plant demand may limit compost effectiveness. (Hari et al., 2024; Rashmi et al., 2023). Furthermore, compost that is not fully mature or improperly applied organic inputs may cause growth inhibition, nutrient immobilization, or physiological stress in plants. (Bhunia et al., 2021) . Therefore, compost quality should be assessed not only by total nutrient content but also by its capacity to support agronomic responses in crops.

A general solution to this problem is to improve compost quality through appropriate feedstock selection, controlled composting processes, and enhanced microbial activity during fermentation. Agricultural residues, livestock wastes, and aquaculture wastes can be processed into organic fertilizers through aerobic composting, co-composting, vermicomposting, and other biological stabilization technologies. These processes allow nutrients and organic carbon to be returned to the soil while reducing linear waste-disposal pathways. (Bhunia et al., 2021; Nenciu et al., 2022; Paradelo et al., 2023). However, composting systems based on heterogeneous wastes still require quality control, particularly with respect to feedstock balance, product maturity, contaminant risks, and consistency of agronomic effectiveness. (Baldantoni et al., 2021; Venkatesham et al., 2025).

In the context of local resources, the combination of cocopeat, shrimp-pond sediment, and chicken manure has potential to serve as the raw-material basis for Cotayam compost. Cocopeat plays an important role as an organic material that supports the physical properties of growing media, particularly water retention, aeration, and media structure. Shrimp-pond sediment represents an aquaculture-derived waste that can be reintegrated into production systems through composting, in line with the concept of aquaculture–horticulture integration based on waste utilization (Nenciu et al., 2022). Meanwhile, chicken manure is a livestock-derived organic waste that can contribute organic carbon and nitrogen when properly processed (Bhunia et al., 2021). The integration of these three materials reflects a locally grounded approach to transforming plantation, aquaculture, and livestock residues into organic fertilizer for melon cultivation.

The effectiveness of Cotayam compost depends strongly on decomposition and nutrient transformation during fermentation. Composting is a biological process driven by microbial community activity through bio-oxidation, mineralization, humification, and stabilization of organic materials. (Durga et al., 2023). In this process, microbial bioactivators or inoculants can be used to improve the efficiency of organic matter decomposition and the quality of the resulting compost. (Manea et al., 2024; Venkatesham et al., 2025). Indigenous bacterial consortia are particularly relevant because they may be more adaptive to the characteristics of specific local waste matrices. However, the effectiveness of microbial inoculation is not universal, as it is influenced by feedstock composition, microbial interactions, resident microbiomes, and environmental conditions during composting and after application to crops. (Aguilar-Paredes et al., 2023; Ibáñez et al., 2023).

Previous studies have shown that compost and microbial bioactivators can improve the quality of organic material, enhance soil biological functions, and support crop productivity. Compost may also provide additional agronomic benefits beyond direct nutrient supply, such as improving soil structure, supplying humified organic matter, increasing microbial activity, and potentially supporting soil conditions that are more suppressive to certain pathogens. (Corato, 2020; Palese et al., 2021; Pilla et al., 2023). However, important gaps remain in understanding the relationship among microbial activation level, compost nutrient enrichment, and crop agronomic response. Many assessments of compost quality still treat nutrient content as the primary indicator, whereas crop response may be shaped by nutrient-release timing, microbial activity balance, and plant physiological demand at specific growth stages. Moreover, microbial inoculant dosage or level is rarely evaluated in an integrated manner within heterogeneous compost matrices and realistic horticultural conditions. (Castiglione et al., 2021; Lau et al., 2022).

Based on these gaps, this study examined Cotayam compost, made from cocopeat, shrimp-pond sediment, and chicken manure, and fermented with Pumakkal, an indigenous bacterial

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bioactivator derived from pineapple liquid waste. This study tested two assumptions: first, that different Pumakkal isolate formulations produce distinct nutrient profiles in Cotayam compost; second, that the highest compost nutrient content does not necessarily yield the best melon agronomic performance. The novelty of this study lies in its emphasis on the divergence between compost nutrient enrichment and crop response, thereby evaluating organic fertilizer effectiveness not only by nutrient concentration but also by plant growth, yield, and fruit quality. The conceptual framework of this study is presented in Figure 1.

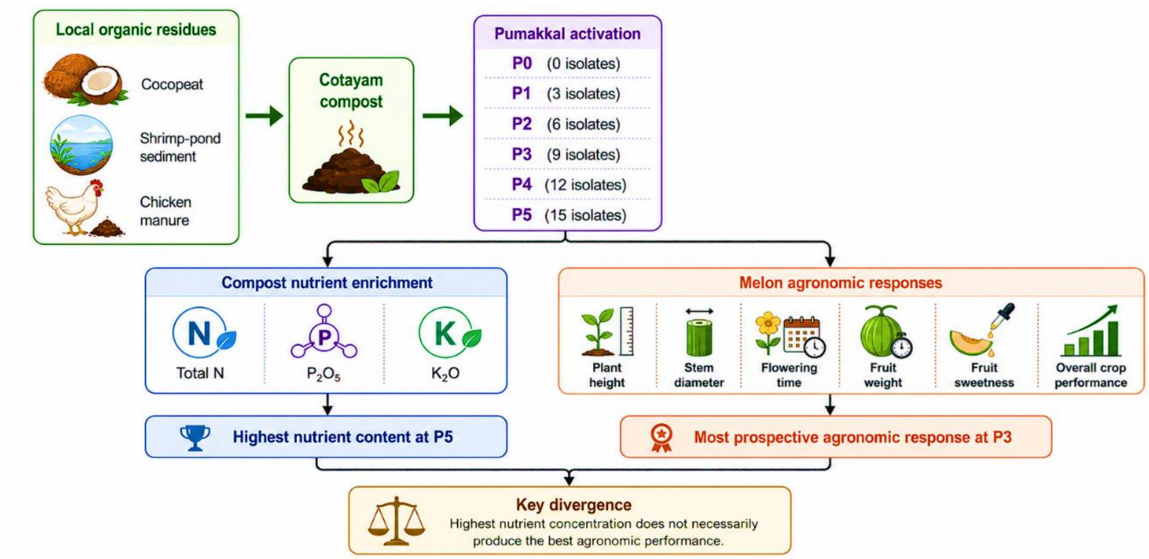

Figure 1. Conceptual framework of nutrient enrichment divergence and agronomic response in melon under Pumakkal-activated Cotayam compost.

METHODOLOGY

Research design and experimental site

This study used a single-factor experimental design to evaluate the effects of different Pumakkal isolate formulations on the nutrient characteristics of Cotayam compost and the agronomic response of melon (*Cucumis melo* L.). The experiment was conducted in Wai Lubuk Village, Kalianda District, South Lampung, Indonesia. The site was relevant because coconut residues, shrimp-pond sediment, and poultry waste are locally available and can be used as raw materials for compost-based fertilizer.

This study used a completely randomized design with one treatment factor, namely the number of Pumakkal isolates used to activate Cotayam compost. The design was selected because the experiment used polybag units under relatively uniform cultivation conditions. Six treatments were tested: P0 without Pumakkal isolates; P1 with 3 isolates; P2 with 6 isolates; P3 with 9 isolates;

P4 with 12 isolates; and P5 with 15 isolates. Each treatment was replicated six times, resulting in 36 experimental units. Each unit consisted of one melon plant grown in a polybag.

Table 1. Treatment structure of Pumakkal-activated Cotayam compost.

Treatment code	Number of Pumakkal isolates	Description
P0	0 isolates	Cotayam compost without Pumakkal activation
P1	3 isolates	Cotayam compost activated with three Pumakkal isolates
P2	6 isolates	Cotayam compost activated with six Pumakkal isolates
P3	9 isolates	Cotayam compost activated with nine Pumakkal isolates
P4	12 isolates	Cotayam compost activated with twelve Pumakkal isolates
P5	15 isolates	Cotayam compost activated with fifteen Pumakkal isolates

Preparation of Cotayam compost and Pumakkal activation

Cotayam compost was prepared from cocopeat, shrimp-pond sediment, and chicken manure. The composting process was carried out using labeled fermentation sacks as containers for aerobic composting. The three organic materials were manually mixed with a hoe until physically homogeneous, and each composting unit was assigned to one of the six Pumakkal activation treatments. P0 was prepared without Pumakkal isolates, while P1, P2, P3, P4, and P5 were activated with 3, 6, 9, 12, and 15 Pumakkal isolates, respectively. Pumakkal, an indigenous bacterial bioactivator derived from pineapple liquid waste, was applied according to the assigned treatment formulation.

The compost mixture in each treatment was sealed in fermentation sacks and aerobically fermented for 1.5 months. During fermentation, the compost was periodically turned and mixed to maintain aeration and uniformity of the material. The composting process was monitored through practical maturity indicators, including temperature, pH, odor, color, moisture condition, and texture. Compost was considered ready for application when it had a brown to dark color, crumbly structure, no offensive odor, was not water-soluble, and had a temperature close to ambient conditions. These criteria were used as practical indicators of compost maturity before the compost was applied to melon cultivation.

Compost maturity was assessed using practical indicators, including temperature, pH, odor, color, moisture condition, texture, and decomposition status. Compost was considered ready for application when it had a brown to dark color, crumbly structure, no offensive odor, was not water-soluble, and had a temperature close to ambient conditions. These indicators were used as practical maturity criteria before the compost was applied to melon cultivation. (Kurniati et al., 2022; Marsono et al., 2023; Zhang et al., 2020).

Laboratory analysis of compost characteristics

After the fermentation period, compost samples from each treatment were collected for laboratory analysis. The analyzed parameters were moisture content, total nitrogen, total P_2O_5, and total K_2O. These parameters were selected because they represent the main macronutrient indicators of compost quality and are directly related to plant growth, flowering, fruit development, and fruit quality. The compost analysis was conducted to compare nutrient enrichment among the six Pumakkal isolate formulations.

The compost nutrient data were interpreted as compositional indicators of fertilizer quality. Moisture content was reported as a percentage, while total nitrogen, total P_2O_5, and total K_2O were reported as percentages to facilitate comparison among treatments. The resulting nutrient profiles were then used to examine whether increasing the number of Pumakkal isolates improved compost nutrient enrichment and whether the nutrient-enrichment pattern corresponded to melon agronomic performance. Because the compost nutrient analysis was used to characterize the chemical composition of each treatment, the moisture content, total N, P_2O_5, and K_2O values were interpreted descriptively and were not subjected to inferential statistical testing.

Melon cultivation and agronomic observation

Melon cultivation was conducted using the melon variety Inthanon (Cucumis melo L.). The cultivation units consisted of 40 × 40 cm polybags filled with a humus-soil-Cotayam compost mixture at a 40:60 ratio. The experiment used 36 polybags, corresponding to six treatments and six replications, with one melon plant grown in each polybag.

Before planting, melon seeds were soaked in lukewarm water for 4 hours to stimulate germination, then incubated for 24 hours until radicles emerged. The germinated seeds were transferred into seedling trays and maintained for 6 days. Uniform seedlings were then transplanted into polybags containing the assigned Cotayam compost treatment and humus soil mixture.

All plants were maintained under similar cultivation practices to reduce non-treatment variation. Plant maintenance included weeding, watering twice daily in the morning and afternoon, stem training, manual pollination, and fruit selection. Fertilization was carried out using Cotayam compost in accordance with the assigned treatment. The compost was applied at a rate of 100 g per plant by soaking it in water and applying the solution to the polybag. Fertilization was conducted in two stages: once every 5 days during the vegetative phase and once every 2 days during the generative phase.

Vegetative growth was measured weekly from 1 to 5 weeks after transplanting. The observed vegetative parameters were plant height, stem diameter, and branch number. Plant height was measured from the base of the stem to the highest growing point. Stem diameter was measured near the lower stem region. The branch number was recorded by counting the visible branches on each plant. Generative and yield parameters included flowering time, fruit weight, and fruit sweetness. Flowering time was recorded as the number of days until the first flower appeared. Fruit weight was measured at harvest, while fruit sweetness was determined as soluble solids using a Brix meter. Harvest was conducted 70 days after transplanting, when fruit maturity was indicated by a yellowish skin color, a distinct fruit aroma, and visible net formation on the fruit surface.

Statistical analysis and interpretation framework

Compost nutrient data were analyzed descriptively to compare enrichment in total nitrogen, P_2O_5, and K_2O across treatments. Agronomic data were analyzed using one-way analysis of variance because the experiment involved one treatment factor with six levels. ANOVA is commonly used in compost-quality and crop-response experiments to test treatment effects on measured variables (Dini & Afriani, 2022; Gallet et al., 2022; Wardani, 2023). Normality and homogeneity of variance were examined before ANOVA.

When ANOVA showed significant treatment effects, Duncan's Multiple Range Test was applied at the 5% significance level. Duncan-based mean separation is commonly used in compost and bioinoculant fertility experiments to compare treatment means after significant ANOVA results (Youssef et al., 2023). The interpretation focused on comparing two response domains: compost nutrient enrichment and melon agronomic performance. This comparison was used to determine whether the treatment with the highest nutrient concentration also produced the best crop response, or whether an intermediate Pumakkal formulation provided a more effective balance between nutrient mineralization, microbial activity, nutrient-release synchronization, and plant demand.

To support the visual comparison between compost nutrient enrichment and overall crop performance, a descriptive normalized agronomic response index was calculated. The index was derived from five main agronomic variables: final plant height, final stem diameter, flowering time, fruit weight, and fruit sweetness. Plant height, stem diameter, fruit weight, and fruit sweetness were normalized in a positive direction because higher values were considered favorable. Flowering time was reverse-normalized because earlier flowering was considered favorable. Each variable was given equal weight, and the composite value was rescaled to a 0–100 index. This index was used only as a descriptive integrative visualization and was not used as a substitute for ANOVA or Duncan's mean separation of individual agronomic traits.

To clarify the experimental sequence, a methodological workflow was developed to connect the preparation of local organic residues, Pumakkal activation treatments, compost nutrient analysis, melon cultivation, agronomic observation, and statistical interpretation. This workflow illustrates how the study was structured to compare nutrient enrichment in Cotayam compost with the agronomic response of melon across different Pumakkal isolate formulations (Figure 2).

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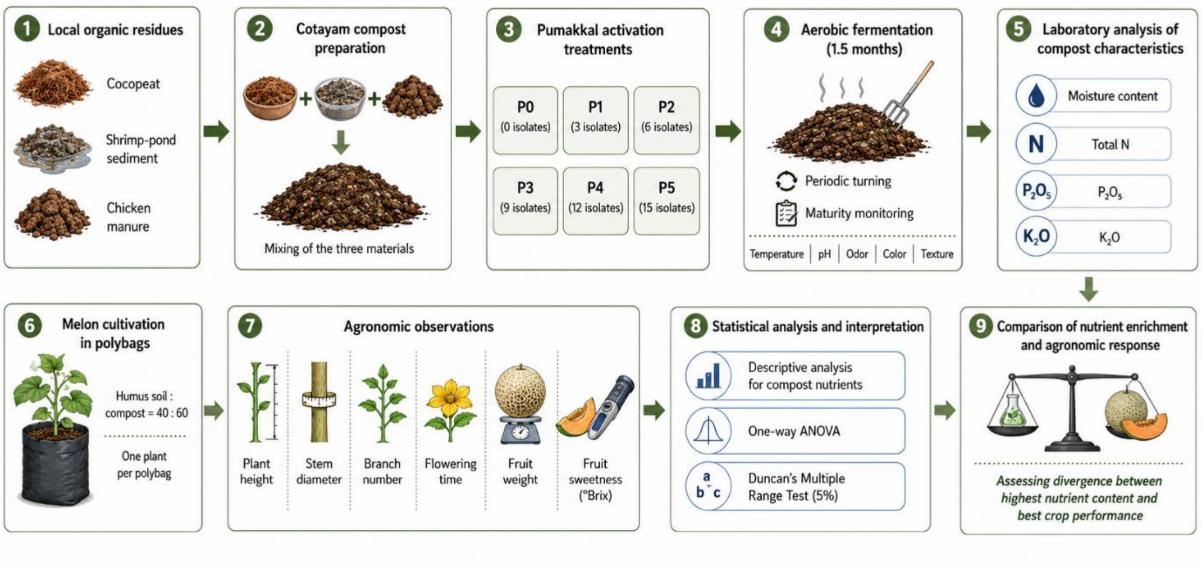

Figure 2. Methodological workflow for evaluating Pumakkal-activated Cotayam compost in melon cultivation.

RESULTS AND DISCUSSION

Nutrient enrichment of Pumakkal-activated Cotayam compost

The nutrient composition of Cotayam compost showed a clear descriptive enrichment pattern across the Pumakkal isolate formulations. Moisture content remained relatively stable among treatments, ranging from 9.60% in P3 to 10.08% in P1. This narrow range indicates that the main difference among compost treatments was not moisture variation, but the composition of total N, P_2O_5, and K_2O. Total N increased from 0.648% in P0 to 2.462% in P5. A similar pattern was observed for P_2O_5, which increased from 0.962% in P0 to 1.870% in P5, and K_2O, which increased from 1.089% in P0 to 2.237% in P5. Therefore, the fifteen-isolate formulation produced the highest measured nutrient content among the compost treatments.

Table 2. Descriptive moisture content and macronutrient composition of Cotayam compost under different Pumakkal formulations.

Treatment	Number of Pumakkal isolates	Moisture content (%)	Total N (%)	P_2O_5 (%)	K_2O (%)
P0	0	10.03	0.648	0.962	1.089
P1	3	10.08	1.258	1.131	1.303
P2	6	9.77	1.698	1.364	1.597
P3	9	9.60	2.098	1.572	1.860

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P4	12	9.68	2.275	1.728	2.058
P5	15	9.77	2.462	1.870	2.237

The increasing values of total N, P_2O_5, and K_2O suggest that higher Pumakkal isolate formulations were associated with greater nutrient enrichment in compost. This pattern is consistent with studies showing that microbial inoculants can support organic matter decomposition, nutrient transformation, and improvements in compost quality, although the magnitude of the effect depends on the feedstock matrix and inoculant strategy. (Matiz-Villamil et al., 2023; Roy et al., 2022; Vurukonda et al., 2024). In the present study, however, the compost nutrient data were used as compositional indicators and interpreted descriptively because no inferential statistical test was applied to the compost nutrient values. Therefore, the finding should be stated as an enrichment pattern rather than as a statistically tested treatment effect (Figure 3).

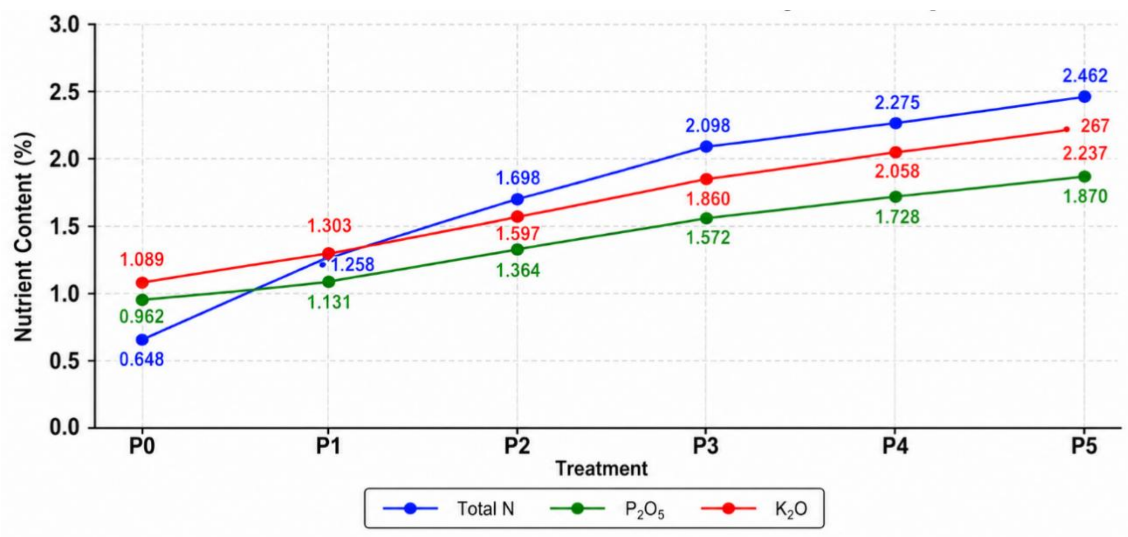

Figure 3. Nutrient enrichment pattern of Pumakkal-activated Cotayam compost. The figure illustrates the increasing trends in total N, P_2O_5, and K_2O from P0 to P5, with the highest nutrient concentrations observed in P5.

The enrichment pattern may reflect the contribution of microbial functional diversity to the decomposition of heterogeneous organic substrates. Cotayam compost combines cocopeat, shrimp-pond sediment, and chicken manure, each contributing distinct organic fractions and nutrient pools. Compost microbiome studies emphasize that compost nutrient properties are shaped by feedstock composition, microbial community structure, and microbial functions during organic matter decomposition. (Aguilar-Paredes et al., 2023). Microbial consortia may also contribute complementary functions, including lignocellulose degradation, proteolysis, phosphate solubilization, and potassium mobilization. (Nester & Saeid, 2022). Thus, the observed nutrient pattern supports the possibility that Pumakkal activation contributed to nutrient transformation during fermentation, but this interpretation should be treated as explanatory rather than confirmatory.

The descriptive nutrient enrichment in P5 is important because it establishes the chemical contrast required to evaluate the study's central hypothesis. P5 produced the highest measured compost nutrient content, yet the strongest agronomic response in melon occurred under P3. This contrast shows that compost nutrient concentration alone was not sufficient to explain crop performance. Compost nutrient content represents the chemical composition of the fertilizer product. In contrast, crop response also depends on nutrient availability, release timing, root uptake, microbial interactions in the growth medium, and plant physiological demand.

Vegetative response of melon to Pumakkal-activated Cotayam compost

Melon vegetative growth responded differently to nutrient enrichment from compost. Final plant height was highest in P3, reaching 167.10 cm, followed by P2 at 162.18 cm and P4 at 160.50 cm. P5, despite having the highest compost nutrient concentrations, produced a lower final plant height of 152.08 cm. Stem diameter showed a similar pattern, with the highest value recorded in P3 at 12.83 mm, followed by P2 at 11.22 mm and P5 at 11.02 mm. Branch number showed a slightly different trend: P4 produced the highest, with 29.00 branches, while P3 remained high at 28.17 branches. These results indicate that P3 produced the most consistent vegetative response, particularly for plant height and stem diameter, while P4 was numerically superior only for branch number.

Table 3. Vegetative response of melon under different Pumakkal-activated Cotayam compost treatments.

Treatment	Number of Pumakkal isolates	Final plant height (cm)	Final stem diameter (mm)	Final branch number
P0	0	150.98	10.63	24.17
P1	3	160.40	10.88	25.83
P2	6	162.18	11.22	26.00
P3	9	167.10	12.83	28.17
P4	12	160.50	10.67	29.00
P5	15	152.08	11.02	26.00

The superiority of P3 in plant height and stem diameter suggests that the nine-isolate formulation provided a more favorable balance between nutrient release and vegetative demand. Melon growth depends strongly on the availability of macronutrients, especially nitrogen for leaf and shoot development, phosphorus for root growth and physiological regulation, and potassium for structural growth and nutrient transport. General agronomic evidence supports that N promotes vegetative development, P supports root and reproductive development, and K contributes to stem development, transport processes, and overall plant vigor. (Belbase & Bc, 2020). In melon systems,

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compost-based substrates and organic amendments have been shown to influence shoot length, leaf number, and stem diameter, although responses vary depending on compost type, substrate properties, and nutrient management. (Aydi et al., 2023; Intana et al., 2023; Raksun et al., 2023).

ANOVA confirmed that the treatment effect was significant for plant height ($F = 2.610$; $p = 0.045$), stem diameter ($F = 13.383$; $p < 0.001$), and branch number ($F = 3.545$; $p = 0.012$), indicating that the observed vegetative differences among treatments were statistically supported.

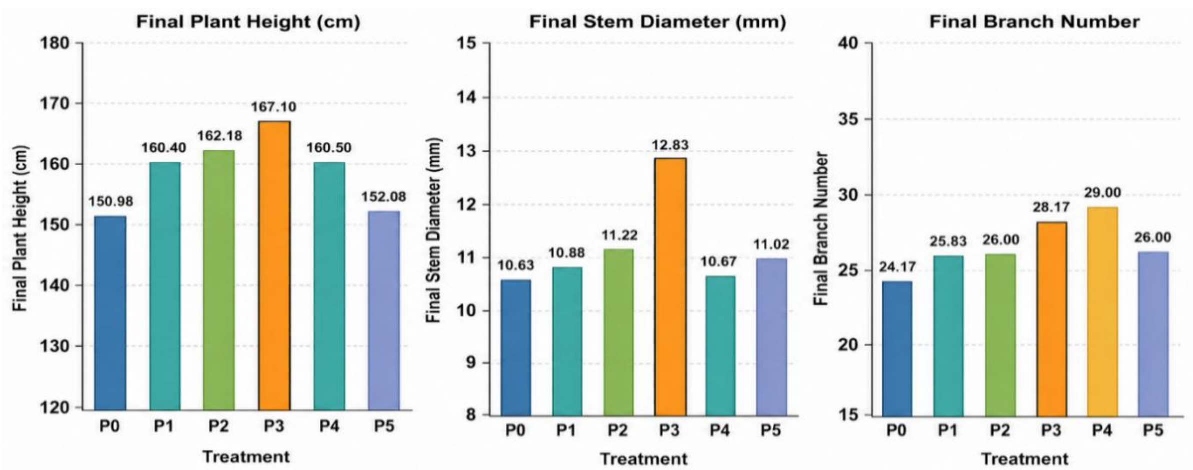

Figure 4. Vegetative response of melon to Pumakkal-activated Cotayam compost. The figure shows that P3 produced the highest plant height and stem diameter, while P4 produced the highest branch number, and P3 remained within the high-response group.

(Diatta et al., 2023; Silva et al., 2024).

The vegetative response observed in P3 may be associated more with a favorable relationship between nutrient availability and vegetative demand than with maximum nutrient concentration alone. Organic amendments release nutrients through microbial mineralization, and this process may support early and mid-stage vegetative development when nutrient release is synchronized with plant demand (Diatta et al., 2023; Silva et al., 2024). However, because nutrient-use efficiency and mineralization rate were not directly measured, this explanation should be interpreted as a plausible agronomic interpretation based on the observed growth pattern (Al-Tawarah et al., 2024; Zondo et al., 2025). The lower plant height in P5, despite its higher compost NPK content, suggests that maximum nutrient enrichment did not translate into maximum vegetative growth. The generative responses were also statistically affected by treatment, with significant differences observed for flowering time ($F = 5.004$; $p = 0.020$) and fruit weight ($F = 5.614$; $p = 0.001$).

This non-parallel response may also reflect the influence of the compost matrix and root-zone balance. Cocopeat contributes to water retention and aeration, while shrimp-pond sediment and chicken manure contribute nutrient pools that require stabilization and mineralization. A treatment with very high microbial complexity may enhance nutrient concentration in the compost, but plant response also depends on nutrient form, microbial competition, root-zone conditions, and the timing of nutrient availability. Therefore, the P3 formulation appeared to provide a more favorable agronomic response than the lower- or higher-isolate formulations, although the biological mechanisms underlying this response were not directly measured.

Generative response, fruit weight, and fruit sweetness

The generative response further confirmed that the best melon performance did not occur under the highest nutrient-content compost. Flowering time was earliest in P3, with first flowering recorded at 13.67 days. P4 followed at 15.83 days, while P1 flowered at 16.50 days, P2 at 17.00 days, P5 at 17.33 days, and P0 at 17.67 days. Fruit weight also reached its highest value in P3, with an average of 1093.17 g. P2 produced the second-highest fruit weight at 963.33 g, followed by P0 at 930.00 g. In contrast, P5 produced only 897.50 g, which was close to P1 and P4. Fruit sweetness, measured as °Brix, was highest in both P3 and P5 at 15.40 °Brix. Therefore, P3 combined early flowering, highest fruit weight, and high fruit sweetness, making it the most agronomically favorable formulation among the treatments.

Table 4. Generative response and fruit quality of melon under different Pumakkal-activated Cotayam compost treatments.

Treatment	Number of Pumakkal isolates	Flowering time (days)	Fruit weight (g)	Fruit sweetness (°Brix)
P0	0	17.67	930.00	14.00
P1	3	16.50	898.33	15.10
P2	6	17.00	963.33	14.70
P3	9	13.67	1093.17	15.40
P4	12	15.83	896.67	15.10
P5	15	17.33	897.50	15.40

The earlier flowering in P3 suggests that the nine-isolate formulation may have supported a more favorable transition from vegetative to generative development. Flowering in melon is responsive to nutrient regime, fertilizer level, and organic nutrient management. Previous studies have reported that organic fertilizer and mineral NPK factors can significantly influence flowering age in melon (Muhamad, 2023), while integrated nutrient management combining organic manures and biofertilizer inputs can affect days to first male and female flowers in muskmelon (Akram et al., 2024). In cucurbit crops, microbial communities combined with bio-organic fertilizer may also accelerate reproductive onset, as shown by earlier flowering in cucumber under a compound microbial community and bio-organic fertilizer treatment (Qin et al., 2020). These studies support the interpretation that microbial activation and organic nutrient management can influence flowering phenology, especially when nutrient supply is synchronized with developmental demand.

The highest fruit weight in P3 may reflect better coordination between vegetative structure and generative sink development. A plant with greater height and stem diameter can support stronger photosynthetic capacity, assimilate transport, and resource allocation to fruit growth. The role of phosphorus and potassium is particularly relevant during flowering and fruit development. Phosphorus supports root function, energy transfer, and reproductive processes, while potassium is involved in sugar transport, osmotic regulation, and fruit quality formation. Studies on melon and cucurbit crops indicate that fruit development under organic fertilization depends not only on total compost nutrients, but also on plant-available nutrient supply shaped by mineralization, rhizosphere microbial activity, and synchronization with reproductive-stage demand (Hidalgo et al., 2022; Rastogi et al., 2020). The P3 formulation likely provided a more favorable agronomic condition for the transition from vegetative growth to fruit development than P5. However, because nutrient-release rate, root-zone nutrient availability, and microbial activity were not directly measured, this explanation remains inferential and should be interpreted in relation to the observed flowering time, fruit weight, and fruit sweetness data.

Fruit sweetness showed a different pattern from fruit weight because P3 and P5 both reached 15.40 °Brix. This indicates that P5 may still have contributed positively to soluble solids accumulation, possibly through its higher K_2O content. Potassium is widely recognized as a key nutrient for sugar transport and soluble solid accumulation in melon and other cucurbits, although its effect can vary with production conditions and interacting stresses (Vurukonda et al., 2024; Xu et al., 2023). The equal sweetness in P3 and P5 suggests that high nutrient enrichment may support certain quality traits, but it did not improve fruit weight or flowering time. Therefore, P3 was agronomically stronger because it combined high sweetness with earlier flowering and heavier fruit.

Divergence between compost nutrient enrichment and melon agronomic performance

The central finding of this study is the divergence between compost nutrient enrichment and melon agronomic performance. P5 produced the highest measured nutrient content in Cotayam compost, with total N of 2.462%, P_2O_5 of 1.870%, and K_2O of 2.237%. However, P3 produced the most favorable agronomic response, including the highest plant height, largest stem diameter, earliest flowering, highest fruit weight, and high fruit sweetness. To visualize this divergence, compost nutrient enrichment was compared with a normalized agronomic response index derived from the main growth, flowering, yield, and fruit-quality variables. This comparison showed that compost nutrient concentration and crop response followed non-parallel trajectories, indicating that higher nutrient concentration in compost did not necessarily result in superior melon performance.

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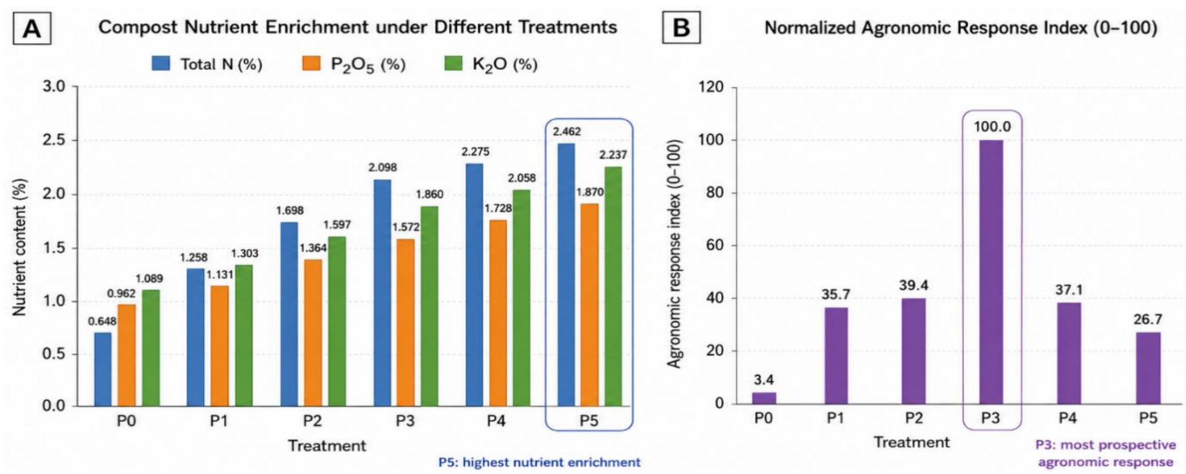

Figure 5. Divergence between nutrient enrichment and normalized agronomic response in melon under Pumakkal-activated Cotayam compost. Panel A shows the descriptive nutrient enrichment pattern of Cotayam compost based on total N, P_2O_5, and K_2O. Panel B shows the normalized agronomic response index derived from final plant height, final stem diameter, flowering time, fruit weight, and fruit sweetness. The figure highlights that P5 produced the highest measured compost nutrient enrichment, whereas P3 produced the highest integrated agronomic response.

The divergence shown in Figure 5 should be interpreted as a descriptive integration of the measured agronomic traits rather than as a separate inferential test. This pattern is consistent with the broader literature showing that higher compost nutrient concentration does not always lead to better crop performance. Compost effects are mediated by nutrient availability, compost maturity, microbial activity, root-zone conditions, and nutrient-use efficiency (Ahmed et al., 2023; Ayed et al., 2022). Nutrient concentration is a useful indicator of compost chemical quality, but plants respond to nutrients that are available, synchronized with demand, and effectively absorbed. Reviews of compost nutrient release indicate that compost may undergo mineralization, immobilization, and slow release, meaning that total nutrient content is not equivalent to immediate plant availability (Orden et al., 2022). Thus, the highest NPK concentration in P5 may represent the greatest chemical enrichment, while P3 may represent the best agronomic balance.

The divergence may also be explained by nutrient-use efficiency and diminishing returns. Field evidence shows that agronomic efficiency can decline as nutrient supply increases, even when microbial inoculation improves nutrient efficiency (Herrera et al., 2024). Integrated nutrient management studies similarly show that strong crop performance can be achieved through improved nutrient cycling and soil enzyme activity without requiring the highest fertilizer input (Al-Suhaibani et al., 2020; He et al., 2024). In the present study, the P3 formulation may have supplied nutrients at a level and release pattern more compatible with melon physiological demand, while P5 may have exceeded the point at which additional nutrient enrichment provided proportional growth or yield benefits.

Nutrient synchrony provides another explanation for the observed pattern. Organic amendments release nutrients through microbial processes, and crop response improves when nutrient availability matches plant demand at critical growth stages. Studies on compost–fertilizer interactions identify nutrient synchrony, priming effects, and balanced nutrient ratios as key mechanisms explaining yield benefits from combined or biologically mediated nutrient systems (Brempong et al., 2022; Essel et al., 2021). At the conceptual level, nutrient synchrony refers to the coordination between soluble nutrient supply generated by soil biota and changing plant nutrient demand (Fontaine et al., 2023). In this study, P3 may have created a better temporal match between mineralization and melon demand during vegetative expansion, flowering, and fruit filling, whereas P5 may have maximized nutrient concentration without optimizing the timing or efficiency of nutrient uptake.

The proposed explanation of nutrient synchrony should be treated as an interpretive framework rather than direct mechanistic evidence. This study did not measure mineral N, available P, exchangeable K, salinity, electrical conductivity, microbial biomass, enzyme activity, or microbial community composition in the root zone. Therefore, the divergence between P5 nutrient enrichment and P3 agronomic performance cannot be attributed to a single confirmed mechanism. It more cautiously indicates that total compost nutrient concentration alone was insufficient to predict melon performance under the conditions of this experiment.

A further possible explanation is that higher microbial-isolate complexity may introduce biological or chemical trade-offs under certain conditions. However, this study did not directly test such trade-offs. Therefore, the lower agronomic response in P5 relative to P3 should not be interpreted as direct evidence of microbial competition, salinity stress, or nutrient immobilization, but as an indication that the highest isolate formulation did not provide the most favorable crop response. Evidence from lettuce grown on compost-amended soils showed that a microbial soil conditioner improved N uptake and yield at half and recommended rates but suppressed yield at twice the recommended rate, demonstrating that excessive bioactivation can reduce performance (Nartey et al., 2021). Similarly, non-linear yield responses can occur when higher input intensity introduces counteracting stresses, reduces efficiency, or disrupts nutrient balance (Mehboob et al., 2021; Yang et al., 2021). Although this study did not directly measure salinity, microbial competition, or nutrient immobilization, the lower agronomic performance of P5 relative to P3 suggests that “more isolates” should not be assumed to mean “better crop response.” The results are therefore best described as a divergence or non-parallel response pattern rather than a formally modeled non-linear curve.

Statistical evidence and agronomic implications of the P3 formulation

The statistical analysis confirmed that Pumakkal-activated Cotayam compost significantly affected the main vegetative and generative parameters of melon. One-way ANOVA showed significant treatment effects on final plant height, stem diameter, branch number, flowering time, and fruit weight. The treatment effect on plant height was significant at $p < 0.05$, while stronger statistical effects were observed for stem diameter, branch number, flowering time, and fruit weight. These results support the interpretation that differences among Pumakkal isolate formulations were not only numerical but also statistically meaningful for key melon agronomic traits.

Table 5. Statistical summary of treatment effects on melon agronomic parameters.

Parameter	**F-value**	**p-value**	**Duncan-based dominant response**	**Statistical interpretation**
Final plant height	2.610	0.045	P3	Significant treatment effect; P3 had the highest mean and differed from the lowest-response treatments
Final stem diameter	13.383	<0.001	P3	Significant treatment effect; P3 formed the superior response group
Final branch number	3.545	0.012	P4/P3	Significant treatment effect; P4 had the highest mean, while P3 remained in the high-response group
Flowering time	5.004	0.020	P3	Significant treatment effect; P3 flowered earliest and was separated from the other treatments
Fruit weight	5.614	0.001	P3	Significant treatment effect; P3 produced the highest average fruit weight
Fruit sweetness	Not tested by ANOVA	Descriptive	P3/P5	P3 and P5 showed the highest observed °Brix value

The Duncan test clarified the agronomic position of the P3 formulation. P3 showed the strongest response for final plant height, stem diameter, flowering time, and fruit weight, whereas P4 produced the highest branch number and P3 shared the highest fruit sweetness value with P5. Therefore, P3 should not be described as the best treatment for every individual parameter, but as the most agronomically favorable formulation based on its combined performance across the main growth, flowering, yield, and quality indicators. This interpretation is important because different agronomic traits may respond differently to the same fertilizer treatment, and treatment evaluation should consider integrated crop performance rather than a single maximum trait value (Olivoto et al., 2022).

The practical implication is that an intermediate Pumakkal formulation may be more effective than the highest-isolate formulation for melon production. The nine-isolate formulation appears to provide a better balance between compost nutrient enrichment and crop demand, while the fifteen-isolate formulation maximized nutrient concentration without producing the strongest agronomic response. This interpretation is consistent with evidence that microbial inoculants can improve nutrient cycling, nutrient availability, and fertilizer-use efficiency, but their agronomic effectiveness remains dependent on microbial compatibility, substrate characteristics, and crop response context (Dagoudo et al., 2024; He et al., 2024; Sharma et al., 2022; Waqas et al., 2025).

These findings indicate that Cotayam compost formulation should be optimized based on agronomic effectiveness rather than nutrient enrichment alone, supporting the use of locally sourced organic wastes as circular nutrient resources for sustainable horticultural production (Fontaine et al., 2023; Tadesse et al., 2021; Telila & Shifera, 2025).

CONCLUSION

This study showed that different Pumakkal isolate formulations produced distinct patterns in Cotayam compost nutrient composition and melon agronomic performance. Increasing the number of isolates was associated with higher measured compost nutrient content, with the highest total N, P_2O_5, and K_2O recorded in the fifteen-isolate formulation. However, the most favorable melon response was achieved with the nine-isolate formulation, indicating that the best agronomic performance was not determined by the highest nutrient concentration alone.

The main finding of this study is the divergence between compost nutrient enrichment and crop response. The nine-isolate formulation may have provided a more suitable relationship between compost nutrient availability and melon physiological demand, although the underlying mechanisms require further confirmation through direct measurements of nutrient-release dynamics, microbial activity, and root-zone conditions. This finding emphasizes that microbially activated compost should be evaluated not only by its chemical nutrient content, but also by its capacity to support crop performance.

This study contributes to the development of locally sourced organic fertilizers by demonstrating the potential of Cotayam compost, produced from cocopeat, shrimp-pond sediment, and chicken manure, as a circular nutrient resource for melon cultivation. It also provides evidence that indigenous microbial bioactivators such as Pumakkal can improve the agronomic value of heterogeneous organic wastes when applied at an appropriate formulation level. Further studies should validate the nine-isolate formulation under broader field conditions, different growing seasons, and more diverse soil environments, while also examining nutrient-release dynamics, microbial community structure, salinity, and root-zone nutrient availability.

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