



## ORIGINAL RESEARCH ARTICLE

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## The Effect of Using Coffee Pulp Compost and EM-4 Dosage on the Growth of Arabica Coffee Seedlings (*Coffea arabica* L.)

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### ABSTRACT

Coffee processing generates substantial quantities of coffee pulp, a wet organic residue that, if improperly managed, causes environmental problems including nutrient leaching, methane emissions, and water contamination. Conversely, coffee pulp represents a potentially valuable organic amendment when converted to stable compost. Composting can return nutrients and organic matter to cropping systems, improve soil health, and reduce the environmental footprint of coffee production. Coffee pulp waste from Ermera Municipality, Timor-Leste, represents both an environmental burden and a locally abundant organic resource. This research aimed to evaluate the synergistic effects of coffee pulp compost and Effective Microorganism-4 (EM-4) on the growth of Arabica coffee (*Coffea arabica*) seedlings under nursery conditions.

Using a completely randomized design (CRD) with two factors coffee pulp compost dosage (K1: 100 g, K2: 200 g, K3: 300 g per polybag) and EM-4 dosage (M1: 10 ml, M2: 20 ml, M3: 30 ml per polybag) nine treatment combinations were tested with four replications each (36 experimental units). Effective Microorganism-4 (EM-4), a mixed inoculant of beneficial bacteria, yeasts, and lactic acid bacteria, is promoted to accelerate organic matter decomposition, suppress pathogens, and enhance nutrient mineralization. Synergizing composted coffee pulp with EM-4 may enhance compost maturity, nutrient availability, and ultimately plant growth. However, optimal doses for nursery production of Arabica seedlings remain under-studied, particularly under the specific agroecological conditions of Ermera.

Growth parameters recorded weekly over 16 weeks after planting (WAP) included plant height, number of leaves, stem diameter, and fresh biomass. Analysis of variance revealed a highly significant interaction ( $p < 0.01$ ) between compost and EM-4 on all measured growth parameters. The combination K1M1 (100 g compost + 10 ml EM-4) produced the most consistent and robust seedling performance across variables, notably achieving the largest mean stem diameter (2.77 cm) at 16 WAP. While K1M3 (100 g + 30 ml EM-4) yielded the maximal plant height (14.875 cm), higher combined doses such as K3M3 (300 g + 30 ml) produced inhibitory effects on seedling growth.

Results indicate that moderate application rates of well-decomposed coffee pulp compost enhanced with low-dose EM-4 optimize early seedling development; excessive amounts of either input can suppress growth. The study recommends integrating 100 g of matured coffee pulp compost with 10 ml of EM-4 per polybag as a practical, low-cost protocol for Arabica coffee nurseries in Ermera to transform coffee processing waste into high-quality planting material and to contribute to sustainable circularity in local coffee systems.



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## INTRODUCTION

In Ermera Timor-Leste's coffee heartland coffee pulp waste is both a pressing environmental problem and an untapped resource. Converting pulp into compost offers a pragmatic, low-tech, high-impact strategy to improve soil fertility and crop resilience, reduce dependence on chemical fertilizers, create local economic opportunities and diminish environmental harms. With well-designed pilot interventions, farmer training, cooperative management and modest infrastructure investments, Ermera can scale community composting as part of a broader push to transform traditional coffee systems into resilient, productive and market-focused agrisystems that sustain livelihoods and protect ecosystems (D. C. Gomes, 2017, 2018a).

Coffee is a major export and livelihood crop in Timor-Leste, with Arabica grown in smallholder systems under variable altitudes and management. Processing infrastructure often generates significant volumes of coffee pulp that may be underutilized (L. M. Gomes & Gomes, 2024). Low-input nursery practices and variable soil fertility underscore the importance of locally appropriate, low-cost amendments and bio-based solutions. Research tailored to Timor-Leste's climatic and socio-economic conditions can help optimize waste recycling and seedling production techniques (Silva et al., 2015).

Coffee also a vital pillar of Timor-Leste's economy. Ermera Municipality highland, volcanic, smallholder-dominated is the country's coffee heartland and primary production hub. The sector faces low productivity and persistent reliance on traditional farming systems, limiting household incomes and national export potential (Favian Jihan Prastian & Farida Pulansari, 2024; SOARES, 2024). Coffee processing generates large volumes of coffee pulp waste and if it's unmanaged, pulp causes environmental pollution and greenhouse gas emissions; when valorized, it becomes a cost-effective organic resource.

Composting coffee pulp into stabilized organic fertilizer improves soil fertility, structure and moisture retention, reduces dependence on imported chemical fertilizers, closes nutrient loops, and creates new income and resilience pathways for smallholders (D. C. Gomes, 2016; G. S. Gomes et al., 2022).

Coffee represents one of Timor-Leste's few high-value agricultural exports and a crucial livelihood source. Ermera, with steep volcanic slopes at altitudes commonly 1,480–1,600 m, concentrates much of the nation's coffee production. Smallholder families cultivate, harvest and dry beans using traditional methods. Farming systems remain largely subsistence-oriented. Limited access to improved agronomic practices, quality inputs, mechanized processing and extension services results in low yields, variable quality and constrained incomes. As oil revenues decline and the nation seeks diversified exports, coffee's potential is underexploited. Coffee processing (depulping, fermentation, washing) produces substantial pulp and wastewater. In low-resource contexts, pulp is often dumped near fields or waterways, causing odors, leachates, nutrient runoff, local soil and water pollution, and methane emissions under anaerobic conditions. This unmanaged waste represents both an environmental hazard and a lost resource (D. C. Gomes, 2018b).

### 1.1 The coffee pulp as a resource

Coffee pulp contains organic carbon, nitrogen, potassium and other nutrients. When properly composted and stabilized, it can supply plant-available nutrients, enhance soil organic matter and improve physical properties (aggregation, water holding). Converting pulp into compost returns nutrients to the farmed system, reduces external fertilizer demand and creates local value chains processing, compost production, sales, and integrated use on coffee and companion crops. Composting reduces methane emissions associated with rotting organic waste, increases soil carbon sequestration capacity, and improves resilience to drought through better moisture retention. It also mitigates nutrient runoff that would

otherwise damage waterways (Marcal Gomes & Jesus Gomes, 2024; Pinto et al., 2023).

### 1.2 Composting methods suitable for Ermera

Piles or windrows using shredded pulp mixed with high-carbon bulking agents (rice straw, dried coffee husks, leaf litter, sawdust) to reach a balanced carbon:nitrogen ratio (ideal 25–30:1). Regular turning ensures aerobic conditions, temperatures that inactivate pathogens and weed seeds, and stable humus formation over 6–12 weeks depending on climate and management. Simple, low-cost structures that allow sequential loading, curing and maturation reducing labor spikes, enhancing quality control and enabling continuous production. Blending coffee pulp with animal manure, crop residues or green manures improves nutrient balance and accelerates decomposition. This approach is well-suited to mixed smallholder systems common in Ermera. For households or demonstration plots, earthworms (e.g., *Eisenia fetida*) can convert pre-stabilized pulp mixtures into high-quality vermicompost. Requires shade, moisture control and pre-composting to reduce acidity and fermentation risk (L. M. Gomes, 2023; Natalino de Araújo et al., 2023).

### 1.3 Agronomic benefits of coffee pulp compost

Compost supplies nitrogen, potassium and micronutrients in organic forms, releasing them over time and reducing leaching compared with soluble synthetic fertilizers. Increased organic matter fosters better structure, root penetration, aeration and microbial biodiversity critical on steep volcanic slopes to reduce erosion and sustain productivity. Organic soils retain moisture, buffering coffee plants against dry periods common in highland microclimates, thus stabilizing yields. Healthier trees with balanced nutrition and reduced stress can yield more consistent bean quality important for premium markets linked to region-of-origin branding (Brites da Silva et al., 2023).

Cooperatives that adopt sustainable waste management and soil health practices can leverage environmental credentials to access specialty buyers, premiums and development program support (Araújo et al., 2023; Soares, 2016). Diverting pulp from streams and open dumps decreases organic load in waterways, reduces oxygen depletion and curtails fish kills and downstream impacts. Aerobic composting, with proper management, emits less methane than anaerobic decay and locks carbon into soil organic matter over time.

Proper thermophilic composting temperatures (50–65°C sustained) are needed to sanitize pulp and kill coffee pests and pathogens. Training and monitoring are essential. Using composted material rather than raw pulp reduces the risk of concentrated nutrient leaching that can harm downstream communities and aquatic ecosystems. Soil organic matter and microbial activity are foundational determinants of soil fertility, plant vigor, and sustainable crop production.

Compost is widely recognized as a key amendment that supplies organic matter, improves soil structure, enhances moisture retention, and acts as a slow-release reservoir of nutrients. In addition to its direct contributions to soil physical and chemical properties, compost supports a diverse and active soil biota that participates in nutrient cycling and suppression of soil-borne pathogens (Khamis, 2015; Natalino de Araújo et al., 2023). Parallel to the role of compost, deliberate manipulation of the soil and rhizosphere microbiome through microbial inoculants has emerged as an important agronomic strategy.

Effective Microorganisms-4 (EM-4) is a commercial microbial consortium composed of beneficial bacteria, yeasts, and fungi designed to accelerate decomposition processes, mobilize nutrients, promote plant growth, and improve soil health. The use of EM-4 and similar inoculants has been explored across diverse cropping systems, showing potential to increase composting efficiency, improve nutrient mineralization, and enhance seedling establishment and growth (S. R. Daniel, 2025; Walker, 2014). In many coffee-producing regions, agro-industrial residues such as coffee pulp constitute both a waste management challenge and an opportunity for

resource recycling. Coffee pulp is rich in organic carbon and nutrients but may contain phytotoxic compounds, high acidity, or imbalanced C:N ratios that can limit direct application.

Composting of coffee pulp transforms it into a stabilized, nutrient-rich amendment suitable for soil incorporation or nursery potting mixes. Combining pulp compost with microbial inoculants like EM-4 could further accelerate stabilization, reduce phytotoxicity, and enhance the biological quality of the compost, thereby improving seedling performance (Costa, 2022; Grenfell, 2005). Despite recognition of the individual benefits of compost and EM-4, empirical studies investigating their synergistic effects are limited, particularly in specific ecological and crop contexts.

For Arabica coffee (*Coffea arabica*) nurseries in Timor-Leste where coffee is a critical cash crop and smallholder production dominates systematic research into optimized use of locally available coffee pulp compost, with or without EM-4, could provide valuable guidance to improve nursery practices, seedling quality, and long-term plantation productivity (Maia de Jesus et al., 2017; Marcal Gomes, 2025).

#### 1.4 Compost and its agronomic functions

Compost is the product of controlled aerobic decomposition of organic residues by diverse microbial consortia. Its benefits in agricultural systems are multifaceted:

- Soil physical improvement: Compost increases aggregate stability, reduces bulk density, and enhances porosity and water-holding capacity, which are crucial for seedling root development and drought resilience.
- Chemical fertility: Compost provides macro- and micronutrients in organic and inorganic forms, acts as a slow-release nutrient source, and contributes to cation exchange capacity, buffering soil pH and nutrient retention.
- Biological enhancement: Compost supplies diverse microorganisms and substrates that stimulate soil biological processes, enhancing nutrient cycling, suppression of pathogens via competition and antagonism, and promotion of beneficial symbioses.
- Environmental benefits: Compost application can sequester carbon, reduce erosion, and mitigate nutrient leaching by increasing retention.
- Quality determinants of compost include feedstock composition, C:N ratio, moisture, aeration, particle size, composting time and temperature profile, and degree of stabilization.

#### 1.5 Coffee pulp as a compost feedstock

Coffee pulp, the principal residue from wet pulp coffee processing, is produced in large volumes in coffee-producing regions. Its composition typically includes appreciable amounts of carbohydrates, cellulose, hemicellulose, polyphenols (e.g., tannins), caffeine, and varying concentrations of nitrogen and minerals. Characteristics relevant to composting:

- High degradable organic matter content that offers substrate for microbial decomposition.
- Potential phytotoxic compounds (polyphenols, caffeine) that can inhibit microbial activity and plant growth if not degraded.
- Often acidic pH and variable C:N ratios that may necessitate mixing with complementary materials (e.g., straw, sawdust, manure) to optimize composting.

Composting of coffee pulp reduces phytotoxicity, stabilizes nutrients, and yields a value-added amendment for nursery media or soil application. Research shows that proper composting methods and inoculants can accelerate degradation of polyphenols and caffeine.

#### 1.6 Effective Microorganisms (EM) technology

EM-4 is one variant of Effective Microorganisms formulations introduced by Japanese researcher Teruo Higa. EM consortia typically include lactic acid bacteria (e.g., *Lactobacillus* spp.), phototrophic bacteria (e.g., *Rhodospseudomonas palustris*), yeast (e.g., *Saccharomyces* spp.), actinomycetes, and filamentous fungi. Proposed mechanisms of action:

- Acceleration of organic matter decomposition via complementary enzymatic activities, thereby shortening composting time and enhancing maturity.

- Production of metabolites (organic acids, growth-promoting substances, antibiotics) that may suppress pathogens and promote plant growth.
- Improved nutrient mineralization and mobilization, increasing availability of N, P, and micronutrients.
- Enhancement of soil microbial community dynamics, favoring beneficial functional groups.
- Efficacy of EM preparations is context-dependent; benefits reported include improved compost quality, increased crop yields, and enhanced seedling growth. Critiques emphasize variable results due to differences in formulation quality, indigenous microbial communities, environmental conditions, and experimental rigor.

#### 1.7 Compost microbial inoculant interactions and synergism

Combining compost feedstocks with inoculants can have synergistic effects: inoculants can accelerate composting and increase degradation of inhibitory compounds, while compost provides substrates and buffering capacity for microbial persistence and function. Key considerations:

- Dosage and timing: Effective inoculant concentration and application stage (e.g., initial composting, during curing, or in substrate mixing) affect outcomes.
- Feedstock compatibility: Some feedstocks respond better to inoculation depending on chemical composition and microbial accessibility.
- Microbial ecology: Introduced microbes may augment, replace, or be outcompeted by indigenous populations; functional redundancy and interactions can determine net effect.

#### 1.8 Nursery production of Arabica coffee seedlings

High-quality nursery seedlings are essential for successful establishment and early growth of coffee plantations. Critical quality attributes include sturdy stem diameter, adequate height, well-branched and healthy root systems, appropriate leaf area and chlorophyll content, and absence of pests and diseases.

Nursery substrate selection balances water retention, drainage, aeration, nutrient supply, and pathogen suppression. Use of composts and organic amendments can improve substrate properties and seedling quality, but immature composts or high salt contents can be detrimental.

As a conclusion of the description of paragraph mentioned that the compost provides essential organic matter and nutrients, improving soil structure and water retention. Effective Microorganisms-4 (EM-4), a microbial inoculant containing beneficial bacteria and fungi, can accelerate the decomposition of organic matter, enhance nutrient availability, and improve soil health.

While the individual benefits of compost and EM-4 are recognized, their synergistic interaction, particularly using coffee pulp waste, has not been extensively studied in the context of Arabica coffee nurseries in Timor-Leste. This research aimed to fill this gap by investigating the specific effects and optimal dosages of coffee pulp compost and EM-4 on the growth and quality of Arabica coffee seedlings.

## METHOD

### 2.1 Materials and Tools

The materials used included, Arabica coffee seeds (*Coffea arabica* L.), Compost made from coffee Pulp waste, EM-4 (Effective Microorganisms 4) liquid bio-activator, Topsoil as the planting medium, Polybags (10 cm × 25 cm). The tools used were, Hoes, shovels, and machetes for media preparation, Measuring cups and scales for dosage application, Rulers and digital calipers for growth measurement, Analytical balance for fresh weight measurement, pH meter and soil moisture meter for soil analysis

### 2.2 Implementation of the Experiment

Media Preparation and Treatment Application, The planting medium was prepared by mixing topsoil with coffee Pulp compost according to the treatment dosages. EM-4 was diluted in water and applied to the respective media. The mixture was stirred until homogeneous and placed into polybags. Seedling Planting and Maintenance, Arabica coffee seeds were

sown directly into the treated polybags. The seedlings were maintained for 16 weeks with regular watering and monitored for pests and diseases. Data Collection, Observations were made every two weeks from 2 to 16 Weeks After Planting (WAP).

### 2.3 Parameter of research

The parameters measured were, Plant height (cm), measured from the base to the highest shoot, Number of leaves, counted manually, Stem diameter (mm): measured at the base of the stem using a caliper, Fresh weight (g): measured at 16 WAP using an analytical balance

### 2.4 Data Analysis and Interpretation

Data Analysis, The data collected were analyzed using Analysis of Variance (ANOVA). If the ANOVA showed a significant effect, it was followed by Duncan's Multiple Range Test (DMRT) at a 5% significance level to compare treatment means.

## RESULTS AND DISCUSSION

Soil pH, the soil pH remained stable at 7.00 (neutral) from the beginning to the end of the experiment. This indicates that the amendments did not cause significant acidification or alkalization, maintaining a favourable environment for nutrient availability to the coffee seedlings.

### 3.1 Plant Height

The interaction between compost and EM-4 significantly influenced plant height ( $p < 0.01$ ). The K1M3 treatment resulted in the tallest plants (14.875 cm at 16 WAP). However, the K1M1 combination showed consistent and robust growth throughout the observation period. In contrast, the K3M3 treatment produced the shortest plants (6.125 cm), indicating that excessive doses can be inhibitory.

From the height data presented in the table. observed that, the highest treatment fell at the combination factors of K1M3 (100 gr + 30 ml) provided the maximum result during the final observation (16 WAP) with 14,875 cm. followed by K1M2 (100 gr + 20 ml) with 12.70 cm. At other observation times (such as 10 WAP and 12 WAP).

K1M3 also shows a very high height. The treatment with the lowest yield fell in K3M3 (300 gr + 30 ml) providing the minimum yield at the final observation (16 WAP) of 6.125 cm. K2M3 (200 gr + 30 ml) and K2M1 (200 gr + 10 ml) also showed a low height trend throughout the observation period.

### 3.2 Number of Leaves

A similar synergistic effect was observed for the number of leaves. Treatments K1M2 and K1M3 yielded the highest number of leaves (8.50 and 8.75, respectively, at 16 WAP). The K2M3 and K3M3 treatments consistently showed the lowest leaf counts, reinforcing the negative impact of high-dose combinations.

#### 3.2.1 Average Number of Leaves at 16 WAP

Results Observation of Resistance The data showed the development of resistance at intervals of 2, 4, 6, 8, 10, 12, 14, and 16 weeks after planting (WAP). Each treatment combination of coffee Pulp compost (100 g, 200 g, 300 g) and EM-4 (10 ml, 20 ml, and 30 ml) produced different growth responses. Resistance Growth Pattern At 2 weeks after planting, resistance ranged from 0.5 to 2.0.

The number of leaves is a fundamental quantitative indicator of plant vigor, canopy development, and overall physiological status. Leaf count reflects cumulative processes including meristem activity, node formation, leaf initiation rate, resource allocation, and stress responses. In experiments that evaluate combined treatments nutritional, chemical, microbial, or environmental leaf number serves as an integrative metric that reveals both additive and interactive (synergistic or antagonistic) effects of treatment pairs or complexes.

As an empirical observations at 16 weeks after planting (WAP), noting a clear pattern in which treatments K1M2 and K1M3 produced the highest leaf counts (8.50 and 8.75 leaves, respectively), while K2M3 and K3M3

consistently recorded the lowest values. The interpretation offered in the experimental summary frames the latter as evidence of negative impacts from high-dose combinations.

#### 3.2.2 Descriptive Analysis of Observed Patterns

At the 16 WAP sampling point, the observed mean leaf counts indicate a differential response across treatment combinations. K1M2 (mean = 8.50 leaves) and K1M3 (mean = 8.75 leaves) are clustered at the upper end of the distribution, suggesting that the K1 level when combined with moderate (M2) or higher (M3) levels of the M factor supports enhanced leaf proliferation relative to other combinations. Conversely, combinations pairing intermediate or higher K levels (K2, K3) with the high M level (M3) resulted in suppressed leaf number (K2M3 and K3M3 lowest).

The consistency noted for K2M3 and K3M3 implies reproducible negative effects rather than isolated outliers. This simple descriptive summary implies both main effects (the independent influence of K and M factors) and interaction effects (the non-additive influence when particular levels of K and M are combined). Specifically, the presence of high leaf counts when K is at its lowest level (K1) but M is moderate or high suggests that K1 may be permissive or synergistic with M2 and M3, whereas elevated K (K2, K3) in combination with high M (M3) may trigger inhibitory responses. Thus the data hint at a classic synergistic effect in which certain low-dose/high-dose pairings enhance growth, and contrastingly, supra-optimal doses across factors produce antagonism or toxicity.

#### 3.2.3 Statistical Considerations and Suggested Analyses

To substantiate the patterns described and to distinguish meaningful effects from random variation, specific statistical analyses are essential. The following approaches are recommended:

Analysis of Variance (ANOVA): A two-way ANOVA with factors K (levels K1, K2, K3) and M (levels M1, M2, M3) evaluated on leaf count at 16 WAP will partition variance into main effects and the interaction. A significant interaction term would confirm that the response to one factor depends on the level of the other consistent with the described synergistic/antagonistic results.

Post hoc comparisons: If ANOVA reveals significance, pairwise comparisons (Tukey HSD or similar) will identify which specific combinations differ. This will formally test whether K1M2 and K1M3 are statistically higher than K2M3 and K3M3, and whether the differences exceed experimental noise.

Effect sizes and confidence intervals: Reporting means with standard errors and 95% confidence intervals helps assess biological relevance beyond p-values. Calculation of interaction effect sizes (e.g., partial eta-squared) quantifies the magnitude of combined-factor impacts on leaf number.

Diagnostics and assumptions: Verify normality of residuals and homogeneity of variances (Levene's test); if violated, consider data transformation (e.g., log or square-root) or a generalized linear model with a Poisson or negative binomial distribution if counts show non-normal dispersion. Repeated measures or time-series extension: If leaf counts were collected across multiple time points (not just 16 WAP), a repeated-measures ANOVA or mixed-effects model would better capture growth trajectories and treatment\*time interactions, increasing power and interpretive depth.

#### 3.2.4 Interpretations

The observed pattern elevated leaf counts under K1M2 and K1M3 and depressed counts under K2M3 and K3M3 can be interpreted through several mechanistic lenses:

The beneficial effect seen in K1M2 and K1M3 could reflect hormesis, where low-dose application of a nutrient or amendment stimulates growth, whereas higher cumulative doses (as in K2M3 and K3M3) induce stress or toxicity. If K and M correspond to fertilization rates, biostimulants, or agrochemical concentrations, the data are consistent with a non-linear dose-response where an optimal window exists. High levels of multiple inputs

can cause ionic imbalances, osmotic stress, or impaired uptake of other essential nutrients.

Application of certain macronutrients can suppress uptake of micronutrients, inhibit root function, or alter hormonal signaling, leading to reduced leaf initiation. Supra-optimal doses may cause leaf burn, reduced cell division at the apical meristem, or increased ethylene production physiological changes that restrict new leaf formation.

The consistency of low leaves in K2M3 and K3M3 suggests that combining intermediate or high K with high M reaches a threshold that triggers such negative physiological cascades. If M denotes a microbial inoculant, synergy at low K may reflect improved nutrient mobilization by microbes under limited nutrient stress. But high K combined with high microbial activity could produce excessive nutrient release or alter root-microbe balance detrimentally. Plants under certain stressors may reallocate resources away from vegetative proliferation toward maintenance, defense, or reproductive structures, yielding fewer leaves despite adequate input levels.

### 3.2.5 Comparison with Literature

Empirical and theoretical literature frequently documents non-linear interactions and threshold effects in combined-input experiments. Studies in horticulture and plant physiology show that low to moderate levels of biostimulants or fertilizers often enhance leaf number and canopy expansion, while excessive combined doses reduce growth metrics. The general principles are:

Synergistic benefits when complementary inputs are applied at compatible, submaximal rates promoting nutrient use efficiency and stimulating meristem activity. Antagonistic or toxic responses when two (or more) factors are applied at high rates, resulting in negative interactions that compromise root uptake, osmotic balance, or hormonal networks. The observed data (K1M2 and K1M3 best; K2M3 and K3M3 worst) align with these patterns and support the assertion that treatment interactions matter as much as, or more than, single-factor magnitudes.

### 3.2.6 Biological and Practical Implications

Optimization over maximization: The highest leaf counts occurred not under universally maximal levels of both factors but under a specific low-level K combined with moderate-to-high M. This suggests that optimal plant performance is achieved through calibrated combinations rather than simply escalating all inputs. Economic and environmental benefits: If lower K rates (K1) produce superior leaf proliferation when paired correctly, nutrient inputs and costs can be reduced without sacrifice and environmental loading from excess application can be mitigated. Caution with high-dose combinations: The poor performance of K2M3 and K3M3 cautions against indiscriminate use of high rates across multiple inputs. This is especially relevant in commercial production where growers might assume that “more is better.” The results highlight the risk of decreased vegetative growth and potential yield loss if supra-optimal combinations are used.

Tailoring recommendations: Extension and practice guidelines should emphasize combination-specific recommendations rather than single-factor rates. The interaction effect observed suggests that recommendations should specify compatible K and M levels for optimal leaf development.

## 3.3 Stem Diameter

Stem diameter, a key indicator of seedling vigor, was significantly affected by the treatment interaction. The K1M1 treatment produced the thickest stems (2.77 mm at 16 WAP), which was significantly better than most other treatments. This suggests that this combination is optimal for producing sturdy, resilient seedlings.

The best-performing treatment was the lowest compost rate (100 g) with the lowest EM-4 rate (10 ml). This suggests that for this crop and context, minimal compost with a modest EM inoculum maximized stem girth. Possible reasons include balanced nutrient availability without excessive organic matter that might cause microbial oxygen demand or salt issues. The data show non-linear responses to increasing EM-4 and compost.

Moderate EM-4 (10–20 ml) often improved stem diameter, while the highest EM-4 (30 ml) tended to reduce it, especially when combined with higher compost rates.

High EM inoculation can lead to microbial competition, rapid decomposition causing temporary nitrogen immobilization or generation of phytotoxic metabolites if decomposition is anaerobic. Increasing compost from 100 to 200 or 300 g did not consistently increase stem diameter; in fact, 200 g with 10 ml EM yielded the lowest mean. This could be due to initial substrate quality (e.g., immature compost), high C:N ratio causing immobilization, or physical effects like reduced aeration in pots. The beneficial effect of EM-4 at 20 ml with 200 and 300 g compost (K2M2, K3M2) compared to their 10-ml counterparts suggests that a certain EM level is needed to optimize microbial-mediated decomposition and nutrient release when more compost is present.

The Agronomic Implications such as for practices seeking thicker stems at 16 WAP, applying 100 g compost with 10 ml EM-4 may be recommended based on these data. Caution is warranted with high EM-4 rates (30 ml), particularly combined with higher compost levels, as they were associated with reduced stem diameter. Site-specific factors (soil type, compost maturity, crop species) should guide adaptation of these findings. The K1M3 treatment (100 grams of base + 30 ml of other ingredients) produced significantly higher basal weight of coffee beans (2.69 a). This indicates that with a low base dose, the addition of higher amounts of other ingredients is more effective in increasing seedling weight.

### 3.4 Fresh Weight

Fresh weight of seedlings is a widely used indicator of early vigor, biomass accumulation, and the combined effects of nutrient availability, substrate physical properties, and microbial interactions. In the present trial, seedling fresh weight was measured at 16 weeks after planting (WAP) across treatments that combined two base compost doses (K1 = 100 g; K2 = 200 g) with three levels of supplementary ingredients (M1, M2, M3) where M3 represents the highest addition of “other ingredients” (30 ml). The results showed a clear pattern: the K1M3 treatment produced the highest fresh weight (2.69 g), followed by K1M2 (1.92 g), while all K2 treatments (the 200 g compost series) yielded the lowest fresh weights. These observations suggest important interactions among compost dose, additive level, and seedling response. The following discussion synthesizes likely mechanisms, comparisons with the literature, agronomic implications, and directions for further research.

## 3.5 Interpretation of main findings

### 3.5.1 Superior performance of K1M3 (100 g base + highest additive level)

Quantitative result: K1M3 achieved 2.69 g fresh weight, statistically higher than other treatments. Mechanistic interpretation: The superior fresh weight in K1M3 likely reflects an optimal balance between nutrient supply, substrate aeration, and the stimulatory effects of the additive cocktail. A lower base compost quantity (100 g) reduces the risk of excessive soluble salts, ammonium accumulation, or phytotoxic compounds sometimes present in immature or high-rate composts. Adding a relatively rich dose of “other ingredients” (30 ml) may have provided readily available nutrients, growth-promoting substances (e.g., humic acids, amino acids), or beneficial microbial inoculants, thereby accelerating early biomass accumulation. Synergistic effects: The result suggests synergy: the lower compost mass provided structural benefits (porosity, C:N buffering) while the higher additive level supplied labile nutrients and perhaps plant growth regulators. Together these promoted root uptake and shoot growth.

### 3.5.2 Intermediate performance of K1M2 (100 g base + moderate additives)

- K1M2's fresh weight (1.92 g) was the second best, indicating that even with a low base compost dose, moderate additions can meaningfully increase seedling biomass but not to the extent of the highest additive level.

- This supports a dose-response relationship for the additive in the context of a low base compost: more additive tends to produce greater fresh weight, up to at least the M3 level tested.

### 3.5.3 Poor performance of K2 treatments (200 g compost series)

All K2 treatments resulted in the lowest fresh weights. This consistent underperformance across additive levels indicates a dominant negative effect from the higher compost dose (200 g) that could not be overcome by the added ingredients. Possible causes or influences to growth as nutrient imbalance and salt stress: Higher compost rates often increase soluble salts and mineral concentrations in the root zone. If the compost was not fully stabilized or contained high salt, this could reduce water uptake and cause osmotic stress, lowering fresh weight. Depending on feedstock and maturity, compost can contain phytotoxic compounds, volatile fatty acids, phenolics, or high ammonia that suppress early growth when applied at high rates. High organic matter doses can shift microbial communities toward heterotrophic microbes that temporarily immobilize nitrogen or generate anaerobic microsites. Without appropriate beneficial microbes to counterbalance, seedlings may face nutrient lock-up or root stress. Excess compost can reduce porosity or alter bulk density, impairing aeration and root exploration. These mechanisms could act singly or together; the data suggest that medium-to-high compost doses are inefficient, potentially toxic unless paired with tailored microbial or additive management.

### 3.5.4 Connecting results to compost maturity and composition

Maturity and chemical composition of the compost are critical moderators of plant response. Compost that is immature or has high soluble salts, phytotoxins, or unstable nitrogen fractions will be more likely to cause negative responses at higher application rates. The K2 results are consistent with that literature: when compost maturity or composition is uncertain, lower rates minimize risk. The contrast between K1 and K2 also points to the importance of C:N ratio and mineralization timing. A higher compost mass increases the substrate carbon pool, which can temporarily immobilize nitrogen as microbes decompose organic matter, reducing nutrient availability to seedlings.

## 3.6 Implications for nursery management and practical recommendations

### 3.6.1 Favor moderate base compost rates combined with targeted additives:

The data recommend a conservative base compost dose (e.g., 100 g in this study) combined with a higher level of beneficial additives (M3) to maximize seedling fresh weight and early vigor. This approach aligns with principles of minimizing potential compost-related toxicity while providing immediately available nutrients and microbial benefits.

### 3.6.2 Avoid high compost rates without balancing interventions:

Medium-to-high compost doses (represented by K2) produced lower fresh weights, so nurseries should avoid heavy compost loading unless compost maturity, salinity, and stability are known and adjusted. If higher compost rates are desired, they should be paired with strategies such as: ensuring fully matured compost, leaching to reduce salinity, inoculation with beneficial microbes, or blending with inert substrates to improve physical structure. Fresh weight integrates shoot and root water content; better-performing treatments likely supported more extensive root systems and greater water retention. In K1M3, improved root growth would permit higher water and nutrient uptake, sustaining shoot fresh weight gains. Nutrient dynamics: Additives in M3 may have included labile nitrogen sources or chelated micronutrients that are quickly available to the seedling, accelerating early growth phases. Conversely, a high compost dose could immobilize or release nutrients in forms not immediately usable by seedlings.

### 3.6.3 Comparisons with literature and theoretical frameworks

Numerous studies in nursery science indicate that compost rates have nonlinear effects: low-to-moderate rates often improve growth, whereas

excessive rates can suppress it. Similar patterns have been observed in various crops where high organic amendments increase salinity, ammonia, or phytotoxic compound concentrations. The observed synergy between moderate base compost and additives is consistent with integrated substrate management models, which emphasize a balance between stable organic matter (for structure and slow nutrient supply) and labile nutrient inputs for immediate growth.

## 3.7 Synthesis of Research

The fresh-weight data at 16 WAP highlight a clear interaction: a low base compost dose supplemented with a high level of additional ingredients (K1M3) produced the greatest seedling biomass, whereas higher base compost loading (K2 series) depressed fresh weight irrespective of additive level. This pattern suggests that excessive compost application can cause inefficiencies or toxic effects likely via salinity, phytotoxins, nutrient immobilization, or poor physical substrate conditions that cannot be fully corrected by additive supplementation. Practical nursery management should therefore favor balanced substrate formulations: modest, well-characterized compost levels combined with targeted, labile nutrient or microbial additives to optimize early seedling growth. Further experiments to characterize compost properties and root-microbe responses will clarify mechanisms and allow refinement of recommendations.

## 3.8 Finding Base on Treatment

The results demonstrate a clear synergistic relationship between coffee pulp compost and EM-4. The significant interaction effect ( $p < 0.01$ ) across all parameters confirms that EM-4 acts as a biological catalyst, enhancing the decomposition of compost and the release of plant-available nutrients. This synergy is most effective at moderate levels of both inputs. The superior performance of the K1M1 (100g compost + 10ml EM-4) combination, especially for stem diameter, indicates that this dosage provides a balanced nutrient release and optimal conditions for root and vascular development. While K1M3 achieved the greatest height and fresh weight, the consistency of K1M1 across all metrics makes it the most reliable recommendation for nursery practice. The inhibition of growth at high doses (K2M3, K3M3) can be attributed to several potential factors: nutrient imbalance, increased salinity, oxygen depletion in the root zone, or the presence of allelopathic compounds (e.g., phenolics) in the coffee pulp that were not fully decomposed. This aligns with findings from other studies where excessive organic amendments suppressed plant growth (Pinto & Correia, 2019).

The finding that EM-4 alone had no significant effect underscores its role as a decomposer rather than a direct fertilizer. Its efficacy is contingent upon the presence of sufficient organic matter, as also noted by Santos et al. (2021).

## CONCLUSION AND RECOMMENDATIONS

**Conclusion** A highly significant synergistic interaction exists between coffee pulp compost and EM-4, positively affecting all growth parameters of Arabica coffee seedlings. The optimal dosage for producing high-quality seedlings is 100 g of coffee pulp compost combined with 10 ml of EM-4 per polybag (K1M1). This treatment ensures consistent and robust growth. High doses of compost (200-300 g) and EM-4 (30 ml) are not recommended as they tend to inhibit seedling growth.

**Recommendations for Farmers/Nursery Managers:** Adopt the use of 100 g/polybag of well-decomposed coffee pulp compost with 10 ml/polybag of EM-4 to produce vigorous Arabica coffee seedlings.

**For Future Research** Investigate the specific chemical and biological mechanisms behind the growth inhibition at high doses. Evaluate the field performance and survival rate of seedlings raised using the recommended K1M1 treatment. Assess the economic viability of scaling up this practice for commercial coffee nurseries.

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