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Microbial–Organic Synergy for Soil Fertility and Growth in *Guadua angustifolia* Kunth

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ABSTRACT

Aims: To evaluate the effects of vermicompost and efficient microorganisms on soil nutrient composition (nitrogen, phosphorus, potassium, and organic matter) and the biometric parameters of *Guadua angustifolia* Kunth.
Material & Methods: A completely randomized factorial design of 2 (presence and absence of efficient microorganisms) **× 3** (20, 30, and 40 % vermicompost dosage), plus a control treatment, was employed, with three replicates. Efficient microorganisms were applied only in three treatments. Soil analyses were performed at the beginning (0 days) and end (90 days) of the experiment for each replicate, and biometric parameters, including shoot height and diameter, shoot number, root length, and survival rate, were assessed.
Findings: Increases in nitrogen concentrations (since 3.66 kg to 16.03 kg)were observed in five treatments, also in potassium (increased from 32.75 kg to 52.86 kg) in six treatments, and organic matter (increased from 7 816.77 kg to 35 812.10 kg) in five treatments, while phosphorus levels decreased in five treatments (lost from 29.70 kg to 49.93 kg). In the same way, the application of vermicompost and efficient microorganisms improved the biometric results, with shoot height of 48.08 cm, shoot diameter of 5.61 mm, 2.80 shoots per plant, root length of 26.32 cm, and a survival rate of 86.67%. In contrast, treatments with only vermicompost yielded values of 37.30 cm, 4.85 mm, 1.67 shoots, 20.28 cm, and 73.33 %, respectively.
Conclusion: Vermicompost mixed with efficient microorganisms improved soil fertility and biometric growth of *G. angustifolia*. Its use is recommended to enhance nursery productivity.

Keywords: Biofertilization; Nursery Management; Organic Agriculture; Reforestation; Substrates.

CITATION LINKS

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Introduction

Bamboo is a grass species belonging to the Poaceae family, comprising approximately 1,400 species worldwide [1]. Of these, 514 are distributed across North and South America [2]. In this way, Peru ranks as the third most biodiverse country in the region, hosting about 60 species [3], with the genus *Guadua* standing out, for its commercial significance, particularly *G. angustifolia*, because this species exhibits remarkable potential for a wide range of applications, including construction, handicrafts, reforestation, medicine, and food production [4]. Despite its beneficial properties, the species faces limitations due to insufficient research on propagation methods that promote optimal biometric development of chusquines, as well as inadequate substrate management practices [5,6,7]. However, factors such as substrate composition, agronomic management, and technological advancements play a critical role in optimizing its viability [8].

Within the framework of sustainable agriculture, efficient microorganisms (EM) have emerged as a promising biotechnological support for nursery applications, because EM are composed of a consortium of beneficial microbial strains, including lactic acid bacteria (*Lactobacillus sp*.), photosynthetic bacteria (*Rhodopseudomonas sp*.), and yeasts (*Saccharomyces sp*.), which collectively enhance substrate conditions [9]. These microorganisms contribute to nutrient cycling by solubilizing phosphorus and potassium, fixing atmospheric nitrogen, and decomposing organic matter into forms that are bioavailable to plants [10]. Moreover, EM produce bioactive compounds such as organic acids, enzymes, and antimicrobial metabolites that suppress soil-borne pathogens and promote plant health [11]. On the same line, their metabolic activity improves soil structure by forming stable aggregates, thereby enhancing aeration, water retention, and root growth. In parallel, vermicompost (VC), an organic substrate derived from the aerobic decomposition of organic residues by the metabolism of earthworms, has demonstrated superior physicochemical properties and nutritional richness compared to conventional substrates [12]; it contributes essential nutrients, humic substances, and beneficial microorganisms that support seedling development and soil fertility [13]. Based on these complementary properties, it is pre-hypothesized that the combined application of EM and VC may produce synergistic effects on soil nutrient dynamics and seedling performance.

As mentioned above, the novelty of this research lies in the absence of prior studies evaluating the combined effect of these two components (EM and VC) on key aspects such as soil nutrient dynamics and biometric parameters in the species under study. In this way, the hypothesis is that integrating EM and VC will significantly enhance soil nutrient availability and biometric characteristics of *G. angustifolia*, offering a better option for improving nursery productivity of *G. angustifolia*. Therefore, the objective of this study was to determine the effects of VC and EM on soil nutrient composition and the biometric parameters of *Guadua angustifolia* Kunth. Additionally, the study emphasizes the nutritional benefits of applying EM to soil, thereby improving crop performance.

Material & Methods

Study Location

The research was conducted at the nursery of the District Municipality of Nueva Cajamarca (UTM, E: 242554.89, S: 9348037.66), as shown in Figure 1. The district belongs to the San Martín department in Peru. Located at an altitude of 856 meters above sea level, the site presents a gentle slope of

approximately 4% with a northeast-facing orientation. With temperatures ranging between 23 and 27 °C, a subtropical climate, a relative humidity of 76 %, and an annual precipitation of 1,500 mm.

Genetic Material Acquisition

The propagation material was obtained from the Innovate Bamboo Planet S.A.C. nursery, located in the district of José Crespo y Castillo, Huánuco. Following the methodology described by Gaddam and Durai [14]. A total of 105 chusquines were transported in a bucket, based on the standard capacity used in previous nursery operations, ensuring adequate ventilation and moisture retention with moist sawdust as a substrate to preserve them during the 12-hour journey to the district of Nueva Cajamarca, as presented in Figure 3-A.

Distribution of Substrates

Following the methodology proposed by Nouri et al. [15], 103.5 kg of agricultural soil was collected from plots near the municipal nursery at a depth of 20 cm. Subsequently, the soil sample was taken to the soil laboratory for nutritional analysis and classification, resulting in the identification of a Cambisol soil order, with a silty clay texture and granular structure. Additionally, 13.5 kg of sand were obtained from the Yuracyacu River, and 40.5 kg of vermicompost (VC) was purchased from the Bio Agroorgánico commercial store, produced from bovine manure and vegetable residues under controlled aerobic conditions. Before use, the VC was sieved and analysed for pH, electrical conductivity, and nutrient content (N, P, K, and organic matter) to ensure consistency across treatments. The substrates — agricultural soil, sand, and VC — were homogenized according to the treatment proportions and distributed into

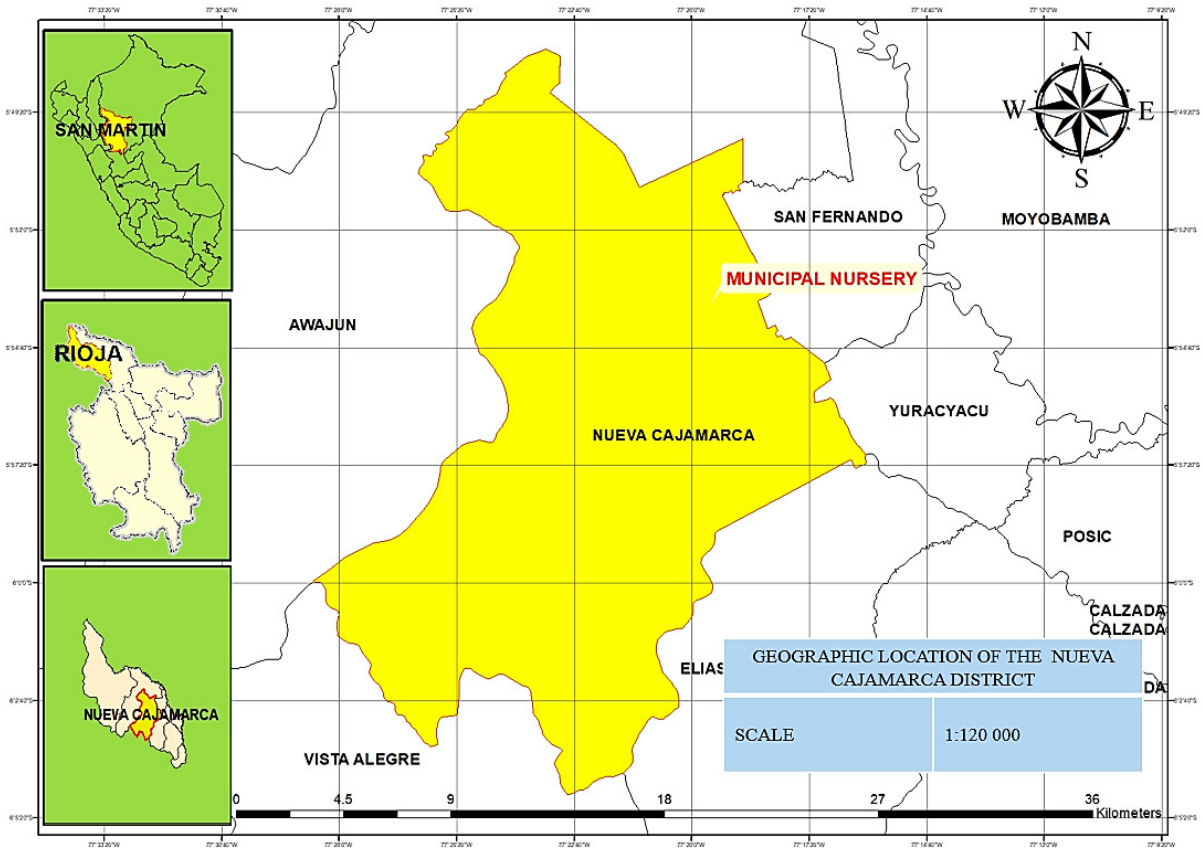

Figure 1) The study area location in Nueva Cajamarca, Rioja, San Martín, Peru.

Table 1) Initial physicochemical characteristics of the treatments

Component	Texture	BD ($g.cm^{-3}$)	pH	EC ($ds.m^{-1}$)	OM (%)	N ($Kg.ha^{-1}$)	P ($Kg.ha^{-1}$)	K ($Kg.ha^{-1}$)
Vermicompost	Sandy Clay loam	1.42	9.77	10.71	15.04	641.758	525.153	1480.527
River sand	Sand	1.70	7.54	0.03	0.23	11.616	161.632	49.319
T0=Agricultural Soil	Silty Clay	1.23	4.95	0.18	2.52	92.916	165.747	212.023
T1=AS (70 %) + VC (20 %) + RS (10 %) + EM	Loam	1.36	8.00	1.54	4.10	92.916	165.748	212.023
T2=AS (60 %) + VC (30 %) + RS (10 %) + EM	Loam	1.36	8.65	2.03		30.694	291.470	237.848
T3=AS (50 %) + VC (40 %) + RS (10 %) + EM	Sandy Loam	1.48	8.84	3.07	6.71	50.384	394.337	443.928
T4=AS (70 %) + VC (20 %) + RS (10 %)	Clay Loam	1.36	8.11	1.64	3.68	55.929	423.749	458.885
T5=AS (60 %) + VC (30 %) + RS (10 %)	Loam	1.38	8.45	2.57	4.02	86.764	516.719	542.025
T6=AS (50 %) + VC (40 %) + RS (10 %)	Sandy Loam	1.45	8.73	2.95	6.27	45.081	396.928	420.787

VC = Vermicompost, RS = River sand, AS Agricultural soil, BD = Bulk density, T0-T6 Treatments 0 to 6. Vermicompost and River sand were included to show their individual composition.

seven experimental treatments, as shown in Table 1 and Figure 3-B. Each treatment was replicated three times, with five *Guadua angustifolia* seedlings per experimental unit, for a total of 105 plants. Treatments included three VC concentrations (20 %, 30 %, and 40 %), each with and without the addition of efficient microorganisms (EM), plus a control (T0) consisting of pure agricultural soil without amendments.

Activation and application of EM

The Effective Microorganisms (EM) used in this study were acquired from the commercial supplier BIOEM S.A.C., which provides a standardized formulation containing specified microbial strains, including *Rhodopseudomonas sp.*, *Lactobacillus sp.*, and *Saccharomyces sp.*, as detailed in the product's technical datasheet and evidenced in Table 2. The EM consortium was pre-selected by the manufacturer (BIOEM); no additional isolation or purification procedures were performed. The selection of the product was based on its demonstrated efficacy in agricultural applications. For activation, the methodology described by Alarcon et al. [16] was followed: 100 ml of cane molasses was diluted in 1,800 ml of water, then 100 ml of EM was incorporated. This procedure aligns with the trials conducted by Safwat and Matta [17], which highlight the crucial importance of a proper fermentation process in optimizing microbial viability. The resulting 2-liter mixture was fermented for 7 days to ensure activation, as shown in

Figure 3-C. Upon completion of substrate preparation, the activated EM solution was applied to treatments T1, T2, and T3 under shaded conditions using a manual sprayer. A total of 4 liters of solution was distributed per substrate, with 50 ml of activated EM per liter of water, consistent with recommendations from recent agricultural trials involving EM-based treatments [18] (Figure 3-D).

Table 2) Composition of effective microorganisms.

Microorganism	Concentration (CFU. mL^{-3})
Rhodopseudomonas sp.	$1.6x10^3$ CFU
Lactobacillus sp.	$4.3x10^4$ CFU
Saccharomyces sp.	$3.3x10^3$ CFU

CFU Colony-forming units. The concentration values ($m.L^{-3}$) and the identification were supplied by the company BIOEM S.A.C. in the product's technical data sheet.

Although Table 2 outlines the primary microbial strains in the commercial EM formulation, the actual consortium likely includes a broader array of microorganisms with complementary ecological roles that are not captured by manufacturer-based, culture-dependent identification methods. Of the species, *Saccharomyces sp*. Get the role to enhance soil conditions through fermentative metabolism, thereby producing organic acids and growth-promoting compounds that induce microbial activity and root growth. As far as *Lactobacillus sp*. is concerned, it contributes to pathogen control by producing antimicrobial metabolites, also facilitating organic matter decomposition and improving nutrient availability. Finally, *Rhodopseudomonas sp*. acts through nitrogen fixation and phytohormone synthesis, promoting plant growth and better root architecture development [19]. Together, these microorganisms interact synergistically to improve soil structure, nutrient dynamics, and the overall vigor of *G. angustifolia* seedlings (Figure 2).

Biometric Parameter Measurement

The measurements of sprout number, sprout height, and sprout diameter were conducted following the methodology of Lárraga et al. [7], with periodic measurements taken every 30 days over three months, based on the standard growth cycle of *G. angustifolia* chusquines, to capture significant biometric changes. In each sampling, the total number of sprouts per seedling was recorded, the height of the tallest sprout was measured, and the thickest sprout of each seedling was assessed. In addition, based on the methodology used by Arancibia and Domínguez [20], the longest root of each seedling was measured at 90 days into the study, as shown in Figure 3-E. Due to the need to preserve *Guadua angustifolia* seedlings for future field trials, destructive biomass measurements were not feasible during the nursery phase.

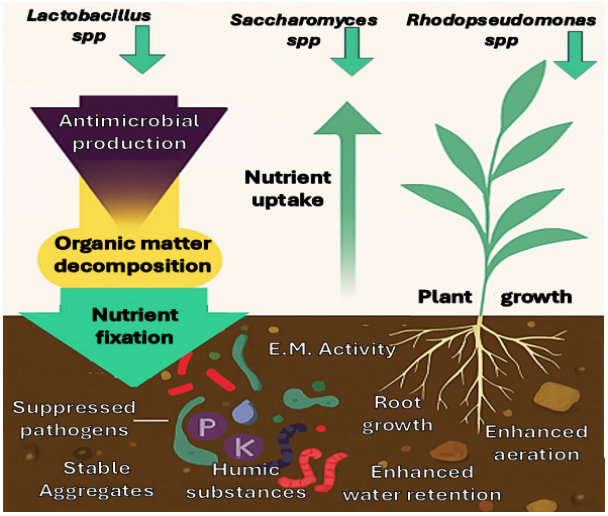

Figure 2) Dynamics of EM in soil and *Guadua angustifolia.*

Survival Estimation and Soil Analysis

The survival rate was calculated as the number of seedlings alive after 90 days divided by the total number of seedlings initially established (Figure 3F). In parallel, soil analyses were conducted in the Soil Laboratory of the Alto Mayo Special Project, following the methodology established by Astonitas et al. [21]. All three replicates for

Figure 3) Chusquines transported in a bucket with special wrapping (A), homogenization of the substrate for treatment (B), activation of EM (C), application of activated EM to the substrate (D), measurement of root length (E), and counting surviving seedlings at 90 days (F).

each treatment were analysed at two distinct time points: the first at the beginning of the study (as shown in Tables 1 and 3) and the second at the end of the study.

Statistical Analyses

The data collected from all evaluated parameters throughout the study, including both soil and biometric variables, were processed using InfoStat software. Prior to performing the analysis of variance, normality was assessed using the Shapiro–Wilk test, and the assumption of homogeneity was verified using Levene's test, both at the 5 % significance level. Once both assumptions were confirmed, an analysis of variance (ANOVA) was applied with a significance level of 5 %, and to compare the means of each analysed parameter, Fisher's Least Significant Difference (LSD) test was also employed at the same significance level.

Findings

Effects on Soil Nutrition

At the conclusion of the study (90 days), a new soil analysis was conducted for each of the three replicates per treatment to identify the physicochemical variation in the substrates resulting from the nutritional demands of the chusquines and the role of efficient microorganisms.

Nitrogen: Treatments T1, T2, T4, and T5 exhibited significantly higher nitrogen concentrations ($F= 17.17$, $p <0.0001$) compared to the initial values (Figure 4A). In contrast, treatments T3 and T6 showed a reduction in nitrogen content by the end of the study.

Phosphorus: On the other hand, a significant decrease in phosphorus concentrations ($F=39$, $p <0.0001$) was observed in five of the evaluated treatments, suggesting limited effectiveness of both VC and EM in enhancing phosphorus

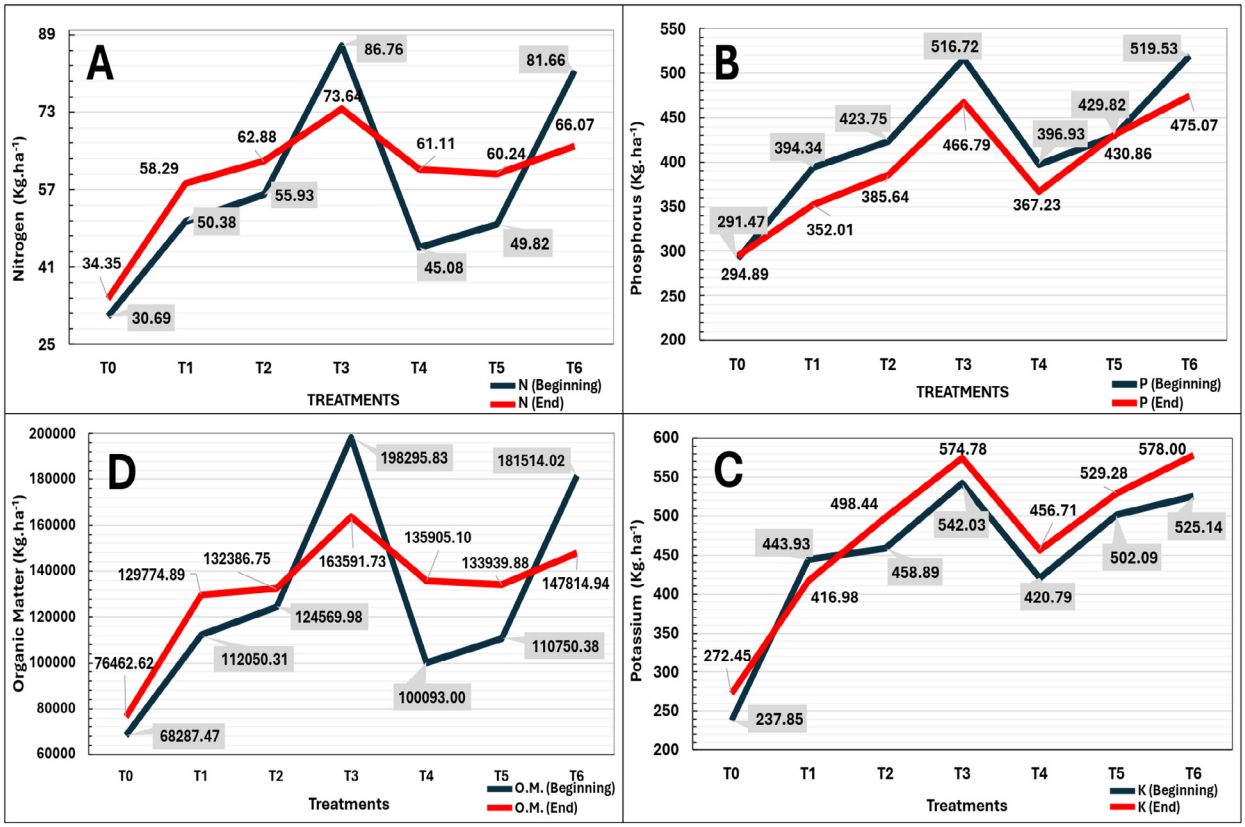

Figure 4) Nitrogen content evolution (A), phosphorus content evolution (B), potassium content evolution (C), and organic matter content evolution (D).
(Parameters of all treatments were measured at 0 and 90 days)

availability (Figure 4B).

1.Potassium: Potassium concentrations increased significantly (F= 21.52, p<0.0001) in six treatments by the end of the experiment (Figure 4C), with all values surpassing those of the control (T0).

2.Organic Matter: Five treatments showed a significant increase in organic matter concentrations (F= 16.32, p<0.0001) at the end of the study (Figure 4D).

Effects on Biometric Parameters

On the other hand, the results obtained for the biometric parameters were progressively evaluated throughout the study, as evidenced in Table 4.

Number of Sprouts: Significant differences (F= 9.94, p<0.0002) were recorded in the number of sprouts for substrates containing 40% VC (with and without EM), 30% VC with EM, and 20% VC without EM (Figure 5A).

Sprout Height: There were significant differences between treatments (F= 53.13, p<0.0001). For example, substrates with 40% VC (with and without EM) and 30% VC without EM exhibited significant differences in sprout height (Figure 5B).

Sprout Diameter: Significant differences (F= 26.53, p<0.0001) in sprout diameter were observed in substrates with 40% VC (with and without EM) and 20% VC with EM (Figure 5C).

Root Length: It increased progressively with higher VC doses and EM application. Significant differences were found (F = 55.72, p < 0.0001), for example, in treatments with 40% VC (with and without EM), 30% VC without EM, and 20% VC with EM (Figure 5D).

Survival Rate: The substrate containing 40% VC plus EM showed significantly higher survival rates (F = 3.37, p < 0.0287) compared to other treatments (Figure 5E).

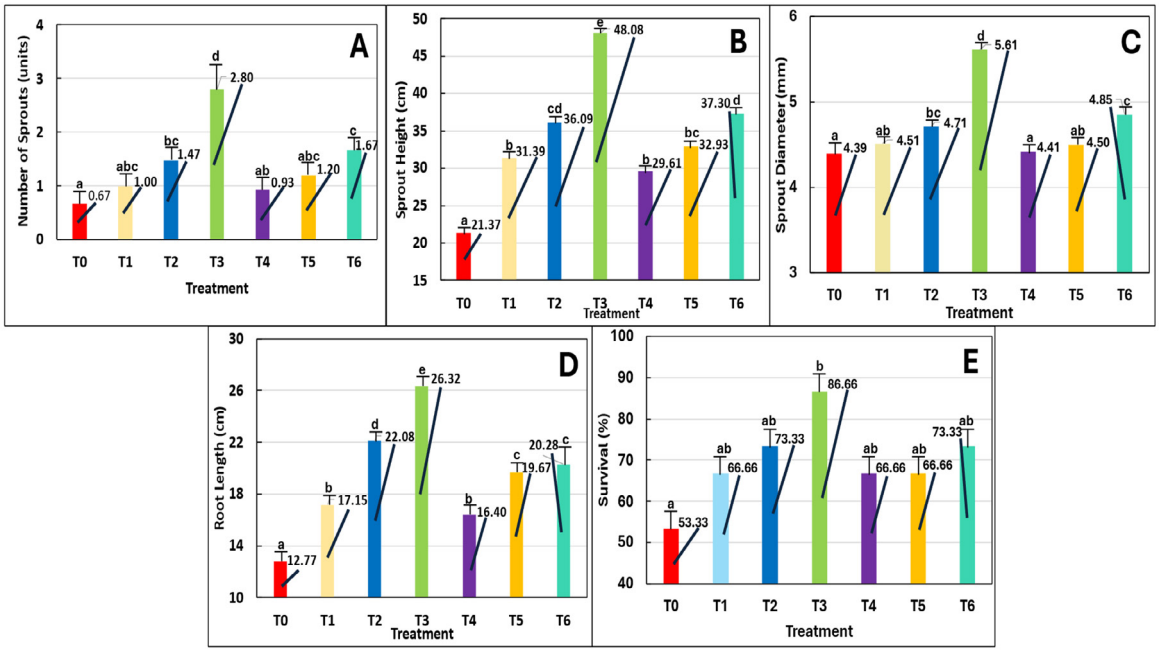

Figure 5) Effect on the number of shoots (A), effect on shoot height (B), effect on shoot diameter (C), effect on root development (D), and impact on survival rate (E).
(Different letters indicate a significant difference in the means of the treatments at the 5 % level)

Table 3) Final physicochemical composition of the treatments.

Component	Texture	BD ($g.cm^{-3}$)	pH	EC ($ds.m^{-1}$)	OM (%)	N ($Kg.ha^{-1}$)	P ($Kg.ha^{-1}$)	K ($Kg.ha^{-1}$)
T0=Agricultural Soil	Silty clay loam	1.28	5.01	0.091	2.998	34.352	294.889	272.446
T1=AS (70 %) + VC (20 %) + RS (10 %) + EM	Loam	1.35	7.84	0.711	4.794	58.292	352.005	416.981
T2=AS (60 %) + VC (30 %) + RS (10 %) + EM	Loam	1.38	8.33	1.194	5.060	62.875	385.643	498.443
T3=AS (50 %) + VC (40 %) + RS (10 %) + EM	Sandy loam	1.48	8.57	1.400	5.502	73.643	466.790	574.784
T4=AS (70 %) + VC (20 %) + RS (10 %)	Loam	1.40	8.03	0.631	4.855	61.114	367.230	456.714
T5=AS (60 %) + VC (30 %) + RS (10 %)	Loam	1.45	8.38	1.247	4.639	60.241	430.862	529.282
T6=AS (50 %) + VC (40 %) + RS (10 %)	Sandy loam	1.50	8.77	1.490	4.950	66.073	475.070	577.996

VC vermicompost, BD = Bulk density, AS = agricultural soil, RS river sand, T0-T6 Treatments 0 to 6.

Table 4) Evolution of biometric parameters over time.

Parameter	Time (Days)	T0	T1	T2	T3	T4	T5	T6
Number of Sprouts	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	30	0.00	0.00	0.00	0.13	0.00	0.00	0.07
	60	0.20	0.40	0.47	1.00	0.33	0.40	0.67
	90	0.67	1.00	1.47	2.80	0.93	1.20	1.67
Sprout Height (cm)	0	19.41	19.31	19.12	19.15	19.12	19.09	19.27
	30	19.74	21.83	22.64	23.87	21.45	22.31	22.75
	60	20.57	25.86	28.49	34.35	24.89	26.83	29.03
	90	21.37	31.39	36.09	48.08	29.61	32.93	37.30
Sprout Diameter (mm)	0	3.95	3.95	3.96	3.95	3.97	4.01	4.05
	30	4.13	4.08	4.17	4.35	4.07	4.12	4.25
	60	4.23	4.25	4.39	4.85	4.21	4.27	4.49
	90	4.39	4.51	4.71	5.61	4.41	4.50	4.85
Root Length (cm)	0	10.67	10.65	10.75	10.68	10.69	10.62	10.65
	90	12.77	17.15	22.08	26.32	16.40	19.67	20.28
Survival (%)	0	100.00	100.00	100.00	100.00	100.00	100.00	100.00
	90	53.33	66.66	73.33	86.66	66.66	66.66	73.33

Discussion

Effects on Soil Nutrition

Nitrogen: The increase in nitrogen concentrations in treatments T1, T2, T4, and T5 aligns with the findings of Murillo et al. [22], who reported that vermicompost contains nitrogen-fixing bacteria that enhance soil fertility. Furthermore, EM are known to stimulate the activity of beneficial microorganisms, facilitating nitrogen fixation by genera such as *Azotobacter vinelandii* [23]. The decrease observed in T3 and T6 (13.12 $kg.ha^{-1}$ and 15.59 $kg.ha^{-1}$, respectively) may be attributed to increased vegetative growth, which elevates nitrogen demand [24].

Phosphorus: Phosphorus is an essential macronutrient; during the early stages of plant development, it is necessary for ATP-mediated energy transfer, nucleic acid synthesis, and cell division [25]. Based on the above, EM have demonstrated the potential to increase phosphorus availability through biochemical mechanisms, such as the release of organic acids and phosphatases, which solubilize unavailable forms of phosphorus [26]. However, the efficiency of these microbial processes is constrained by environmental and biological factors, including soil pH, adsorption, and dynamics of organic matter, which collectively influence phosphorus bioavailability. In vigorous vegetative growth, as observed in *G. angustifolia* seedlings, the rate of phosphorus uptake may exceed microbial solubilization capacity, leading to nutrient depletion. The decline in phosphorus concentrations in the treatments of this study suggests that EM alone was insufficient to meet the species' high phosphorus demand.

Potassium: According to Restrepo et al.

[27], potassium becomes associated with particles such as organic matter through adsorption processes, which explains its higher content in all treatments compared to T0 (control treatment). Moreover, Ordóñez et al. [28] reported that EM contain potassium-solubilizing bacteria that can increase potassium availability by up to 395 %. This suggests that the substrate used likely contained such bacteria, thereby enabling nutrient solubilization and contributing to the observed increase in potassium concentrations.

Organic Matter: The increase in organic matter content is attributed to the substantial input of VC, because it inherently contains high levels of partially decomposed organic matter. Furthermore, its biological decomposition is accelerated by earthworms [29] through their digestive processes, which fragment complex organic compounds into simpler, more stable humic substances [30]. This not only improves soil organic carbon but also enhances its structure and nutrient retention capacity, thereby contributing to the observed increase in organic matter concentrations across most treatments.

Effects on Biometric Parameters

Number of Sprouts: Similar results were obtained by Ticona and Mamani [31], who reported two shoots. However, a higher quantity of sprouts was obtained by Alvarado et al. [32], who reported 9.67 shoots, and Bonilla et al. [33] obtained 9.07 shoots. On the other hand, lower shoot counts were reported by Gallardo et al. [34] with only 0.75 shoots and by Lárraga et al. [7] with an average of 1.29 shoots. The low results may be attributed to the excessive organic matter in the substrates, as mentioned by Acosta et al. [35], who observed that incorporating up to 80 % VC can lead to nutrient imbalances and reduced aeration, ultimately delaying plant development.

On the other hand, studies carried out by Flores et al. [36] showed that greater sprout production was accomplished using lower proportions of organic matter in substrates, specifically 33 % rice husk combined with EM like mycorrhizal fungi, because this kind of microorganisms are known to improve nutrient uptake and develop a better structure in the substrates, also promotes more favourable conditions for sprout growing [37]. It highlights the importance of adequately managing organic matter doses and EM composition during substrate preparation [38]. Furthermore, the EM applied in this study significantly increased the number of shoots produced by the chusquines, increasing them by 167.7% compared to treatments without EM application.

Sprout Height: Effective Microorganisms (EM) enhance early plant growth through their diverse microbial composition, which supports nutrient solubilization, hormonal activity, and root development [39]. Their effectiveness and positive impact on shoot elongation and biomass accumulation have been demonstrated in crops such as sweet corn and legumes, especially when combined with organic substrates [40, 41]. In contrast, lower shoot growth observed in treatments using molasses residue or high vermicompost concentrations [7, 34] may result from suboptimal substrate conditions that impair nutrient uptake and aeration.

Sprout Diameter: Authors such as Gallardo et al. [34] reported comparable values (5.3 mm) with 80% vermicompost. Although the applied dose was considerably high, it positively affected stem diameter growth in the seedlings. However, it did not have a favourable effect on other biometric parameters, such as height and number of shoots. In contrast, other researchers obtained smaller diameters, such as Ticona and Mamani [31], who achieved 3.35 mm using pure agricultural soil, and [7], who recorded 2.6 mm using

molasses residue and cattle manure. According to Tanya and Leiva [9]. EM promotes increased plant diameter and enhances overall plant vigor, which may explain why the diameter observed in the present study was significantly greater than those reported by other authors.

Root Length: Authors such as Ticona and Mamani [31] obtained comparable results (26.28 cm), as did Lárraga et al. [7] (25.57 cm). According to Naik et al. [40], EM directly influences root development by boosting rhizosphere microbial activity, promoting nutrient solubilization, organic matter decomposition, and enzymatic activity. Through these processes, root architecture and biomass accumulation are developed by improving soil structure and aeration, thereby facilitating the availability of essential nutrients such as nitrogen and phosphorus [41]. The mentioned results above align with the present findings, as T3 (with EM + 40 % VC) outperformed T6 (without EM + 40 % VC) by 29.79 %. Therefore, it confirms that EM significantly improved root development in chusquines of *G. angustifolia*.

Survival Rate: Authors such as Nouri et al. [15] reported comparable results (70 %) with 25 % vermicompost; however, the results of the present study were significantly superior in T3, attributed to EM's positive effect on seedling survival [42]. Furthermore, the proportion of VC (40 %) used is considered acceptable given its organic matter content [35]. On the other hand, Gallardo et al. [34] reported significantly lower survival rates (53.2 %) with 80 % VC, as did Lárraga et al. [7], who achieved a survival rate of 55.52 % with cachaza and goat manure. The difference between authors is attributed to the excessive doses of organic matter employed in the studies; the excess of organic matter not only affects survival rates but also other biometric parameters, such as the number and length of shoots.

Conclusion

In conclusion, the use of EM and balanced proportions of VC has a positive influence on soil quality by increasing nitrogen, potassium, and organic matter content. The inputs also enhance shoot number, height, and diameter, positively affect root length, and mitigate the adverse effects associated with excessive organic matter content. For the reasons above, the results support the hypothesis that integrating EM and VC will significantly improve soil nutrient availability and the biometric parameters of *G. angustifolia* Kunth, offering a viable strategy for improved nursery productivity and sustainable propagation of the species. The findings highlight the significance of using properly balanced substrate compositions and demonstrate the synergistic interaction between EM and VC in improving the propagation success of *G. angustifolia*. Thus, this study contributes a scientifically grounded framework for improving nursery practices and promoting sustainable alternatives for propagation. Among the evaluated treatments, the combination of 40% VC with EM (T3) was identified as the most effective, achieving superior results in both soil nutrient enrichment and biometric development. Future research should test other levels of the substrate and extend the investigation through field trials, assessing long-term plant development, soil microbial dynamics, and broader agroecosystem impacts to support the scalability and ecological relevance of EM and VC integration in bamboo-based reforestation and agroforestry systems.

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