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Effect of the humus-to-sediment ratio on the germination and initial growth of cocoa (*Theobroma cacao*)

Efecto de la relación humus: sedimento en la germinación y crecimiento inicial de cacao (*Theobroma cacao*)

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Abstract

Agrochemical contamination and soil degradation demand the search for organic biofertilizers that guarantee the sustainability of cacao cultivation. This research evaluated the nutritional quality of a humus produced from cattle manure and water hyacinth (*Eichhornia crassipes*), as well as its effect on the initial stage of Fine Aroma National Cacao. The experimental design consisted of five treatments with different proportions of sediment and humus, analyzing chemical variables, presence of heavy metals, and biological response. The results showed that pure humus possesses the highest concentration of macronutrients, with potassium values reaching 7306.79 mg kg^{-1}. However, in the germination phase at nine days, 100% humus totally inhibited seed emergence, while the sediment control and the mixture (1:3) led with 62% and 61% success, respectively. At thirteen days, the humus treatment (100%) overcame the initial dormancy, reaching 95% germination. Regarding Cd, it remained at permissible levels of 0.98 mg kg^{-1}, lower than 1.00 mg kg^{-1} in all substrates. These results, obtained at the initial level of plant growth, constitute an experience for reducing the excessive use of chemical fertilizers, thereby reducing their harmful impact on the environment. In addition, organic cacao, being free of chemical residues, offers a healthier product, promoting sustainable agricultural practices that benefit the community and the ecosystem.

Keywords: biofertilizer, humus, substrates, *Theobroma cacao*

Resumen

La contaminación por agroquímicos y la degradación de suelos exigen la búsqueda de biofertilizantes orgánicos que garanticen la sostenibilidad del cultivo de cacao, la presente investigación evaluó la calidad nutricional de un humus producido a partir de bovinaza y lechuguín (*Eichhornia crassipes*), así como su efecto en la etapa inicial del Cacao Nacional Fino de Aroma, el diseño experimental consistió en cinco tratamientos con diferentes proporciones de sedimento y humus, analizando variables químicas, presencia de metales pesados y respuesta biológica. Los resultados mostraron que el humus puro posee la mayor concentración de macronutrientes, con valores de potasio que alcanzaron los 7306,79 mg kg^{-1}. Sin embargo, en la fase de germinación a los nueve días, el humus al 100% inhibió totalmente la emergencia de las semillas; mientras que el control de sedimento y la mezcla (1:3) lideraron con un 62% y 61% de éxito, respectivamente. A los trece días, el tratamiento de humus (100%) superó la latencia inicial alcanzando un 95% de germinación. En cuanto al Cd, se mantuvo en niveles permisibles de 0,98 mg kg^{-1}, menor a 1,00 mg kg^{-1} en todos los sustratos. Estos resultados obtenidos, a nivel inicial del crecimiento de plantas constituye una experiencia, para disminuir el uso excesivo de fertilizantes químicos, reduciendo así su impacto nocivo en el medio ambiente. Además, el cacao orgánico, al estar libre de residuos químicos, ofrece un producto más saludable, promoviendo prácticas agrícolas sostenibles que benefician a la comunidad y al ecosistema.

Palabras clave: biofertilizante, humus, sustratos, *Theobroma cacao*

1. Introduction

The accelerated pollution of soil and water, resulting from effluent discharge and the intensive application of pesticides, herbicides, and chemical fertilizers, exerts a high environmental impact and compromises human health. Given this scenario, further studies aimed at finding biodegradable organic raw materials that allow the development of biofertilizers with documented nutritional quality are required. The quality of an organic fertilizer is determined according to the target agroecosystem, so it is imperative to identify, in its characterization, the available nutritional content and the substrate properties that condition the vegetative response (Reyes-Pérez et al., 2018; García Gutiérrez & Félix Herrá, 2014). The substrates for these fertilizers are generally selected from local agricultural sectors, being classified according to their origin as agricultural, livestock, forestry, or urban; consequently, the properties of the final product reflect the characteristics of the environment involved (Alvarez Ticllasuca et al., 2022; Muñoz-Rengifo et al., 2024).

The humus produced from cattle manure residues and water hyacinth (*Eichhornia crassipes*) represents a biotechnological option for organic cacao cultivation due to its potential as a source of essential macronutrients such as N, P, and K, which directly affect key physiological processes in the initial stages of plant development. From an agronomic standpoint, nitrogen favors protein synthesis and leaf development, phosphorus is indispensable for energy transfer and the establishment of the root system, and potassium regulates cell turgor and stomatal opening (Marschner, 2012). Cattle manure provides organic matter of high biological availability, while water hyacinth, an aquatic plant with a high mineral absorption capacity, complements the nutritional profile needed for seedling establishment (Murillo Montoya et al., 2019; Gutiérrez et al., 2025). The incorporation of river sediment as a substrate component can improve the physical structure and aeration of the mixture, factors that are determinant for emergence and root anchorage during germination (Oviedo-Ocaña et al., 2017; Rivas-Nichorzon & Silva-Acuña, 2020).

Within the framework of current knowledge, the partial substitution of agrochemicals with locally sourced organic inputs constitutes a viable agronomic alternative to reduce dependence on chemically synthesized fertilizers, contributing to the maintenance of soil fertility in cacao production systems (Quevedo Guerrero et al., 2020). However, the question remains as to which is the optimal humus-to-river-sand ratio that maximizes biological success in the initial phenological stages of Fine Aroma National Cacao [FANC], without compromising seedling development.

The hypothesis put forward in this research is that the combination of humus produced from cattle manure and water hyacinth with river sediment, in determined proportions, positively influences the germination and initial growth of FANC seedlings compared to suboptimal mixture proportions, with the humus:sediment ratio being the determining factor of the observed vegetative response. FANC is a type of cacao internationally recognized for its distinctive organoleptic characteristics and genetic purity, under the classification criteria of the International Cocoa Organization (ICCO, 2024). The study design includes the nutritional characterization of the substrates and the evaluation of the vegetative response under different mixture proportions; therefore, the objective of the present research was to determine the effect of the humus:sediment ratio on the germination and growth of FANC seedlings in order to select the treatment with the highest productive efficiency.

2. Materials and Methods

The research was conducted at the La Pastora Sol Farm (Latitude: 0° 49’40.7”; Longitude: W 80° 11’ 36.76”), located in the Chone-Tosagua-Calceta triangle area in Manabí, Ecuador. The site presents edaphoclimatic characteristics typical of a tropical dry forest, with an average temperature of 26 °C and a relative humidity of 80%. The experiment was carried out under controlled nursery conditions to ensure homogeneity in light exposure and irrigation (Jones et al., 2025).

2.1. Biological material and inputs

The stabilization process was carried out through vermicomposting, for which 250 earthworms of the species *Eisenia foetida* were used per experimental unit, acquired from a company specialized in vermiculture. The mixture of cattle manure and water hyacinth was distributed into nine wooden experimental units (60 cm × 50 cm × 20 cm), and the process was maintained for seven months. During this period, periodic mixing of the substrate was carried out in order to guarantee adequate aeration and the moisture conditions necessary for the preservation and activity of the earthworms. At the end of the stabilization period, the humus used as the base substrate in the experimental treatments was obtained. Washed river sand (sandy loam texture) was extracted from alluvial deposits of the Carrizal River to be used as the control and base for the mixtures.

2.2. Experimental design

The five treatments included in the study are presented in Table 1. Regarding the smaller number of bags for T5, this is explained by the smaller volume of organic fertilizer initially used at the time the 250 earthworms were added. However, a higher humus production sufficient to reach the same number of bags was not achieved.

This condition is recognized in the experimental statistics literature (Montgomery, 2013), which notes that “it is possible that the experimenter originally planned a balanced experiment, but because of unforeseen problems encountered while running the experiment, resulting in the loss of some observations, ends up with unbalanced data” (chap. 15.2). Consequently, the statistical analysis was carried out using procedures appropriate for unbalanced data, considering that T5 has lower statistical power due to its smaller number of replicates.

For the chemical characterization of the substrates, the N, P, and K content was determined, and the presence of Cd and Pb was quantified by atomic absorption spectroscopy [AAS]. The laboratory protocols are based on Acuerdo Ministerial 097/A of the Ministry of Environment and Energy.

The dependent variables measured were Germination percentage: evaluated at 9 and 13 days post-sowing; and Growth: measured with a digital caliper at 9 and 14 days.

2.3. Statistical analysis

Data processing and analysis were performed using the specialized statistical software Minitab version 18.1 (Minitab LCC, 2026). Descriptive results were represented by the mean and standard deviation.

Table 1. Description of the treatments evaluated in the trial.

Treatment	Bags	Sediment:Humus	Proportion (%)
T1	50	Sediment	100:0
T2	50	Sediment:Humus	1:1
T3	50	Sediment:Humus	1:2
T4	45	Sediment:Humus	1:3
T5	22	Humus	0:100

3. Results and Discussion

Table 2 presents the values corresponding to the N, P, and K concentrations determined for each of the treatments evaluated. The results show that T1 exhibited the lowest concentrations of the three macronutrients, characterized by the absence of detectable nitrogen (0.00 mg kg^{-1}), as well as very low contents of P (276.8 mg kg^{-1}) and K (0.98 mg kg^{-1}).

On the other hand, the progressive increase in the proportion of organic matter was associated with an increase in macronutrient availability, with the maximum value observed in T5, corresponding to the 100% humus control. This treatment presented the highest concentrations in the study, reaching 640.00 mg kg^{-1} of N, 3,344.00 mg kg^{-1} of P, and 7,306.79 mg kg^{-1} of K; however, these levels caused a delay in the initial phases of germination.

In the analysis of the chemical composition of the substrates, it was observed that the N, P, and K content increased proportionally to the humus concentration in the mixture. This nutritional enrichment is characteristic of the humus produced from cattle manure and water hyacinth (*Eichhornia crassipes*), which act as concentrated sources of macronutrients essential for cacao (Palma et al., 2018). The high K load in the treatments with a higher volume of humus is directly related to the bioaccumulation capacity of this aquatic plant during its composting process (López Jerves, 2012). However, the chemical superiority observed

Table 2. N, P and K concentration (mg kg^{-1}) according to organic substrate treatment.

Treatments	N	P	K
T1	0.00	276.8	0.98
T2	320.00	1,948.00	2,579.07
T3	160.00	2,928.00	3,866.36
T4	160.00	2,736.00	4,821.27
T5	640.00	3,344.00	7,306.79

in the proximate analysis did not directly translate into biological success during the initial stage (Vences-Martínez et al., 2025).

3.1. Germination dynamics (9 and 13 days)

Figure 1 shows the germination percentages obtained for FANC seeds during two evaluation times. The results reveal differences in the germinative response associated with both the evaluation time and the proportion of organic matter present in the substrates.

In the initial germination phase at 9 days for FANC seeds, it was observed that the 100% sediment or washed river sand control (T1) and the sediment-humus mixture in a 1:3 ratio (T4) obtained the highest success percentages, with 62% and 61% respectively, because the sandy loam texture of the soil provides the optimal aeration and drainage that the cacao embryo requires for its initial emergence without suffering water stress (Mendoza Intriago et al., 2024). Despite the nutritional deficiency reported in the base soil, its physical structure prevents waterlogging, a factor that tends to inhibit germination in media with excessive organic load (Gracia Valenzuela et al., 2019). Meanwhile, the strategic integration of humus derived from cattle manure and water hyacinth in treatment T4 suggests that a balance between the supply of macronutrients (N, P, K) and the porosity of the sediment favors the enzymatic activation of the seed (Schmidt et al., 2025).

This result, however, constitutes the central paradox of the experiment: the substrate with the highest macronutrient concentration, 100% humus (T5), with K = 7306.79 mg kg^{-1} and P = 3344.00 mg kg^{-1}, was the only one that totally inhibited emergence at 9 days (0%). This inhibition cannot be explained by nutritional deficiency, but rather by the opposite effect: the high density of mineral salts generates an external osmotic potential more negative than the embryo's internal water potential, preventing the water imbi-

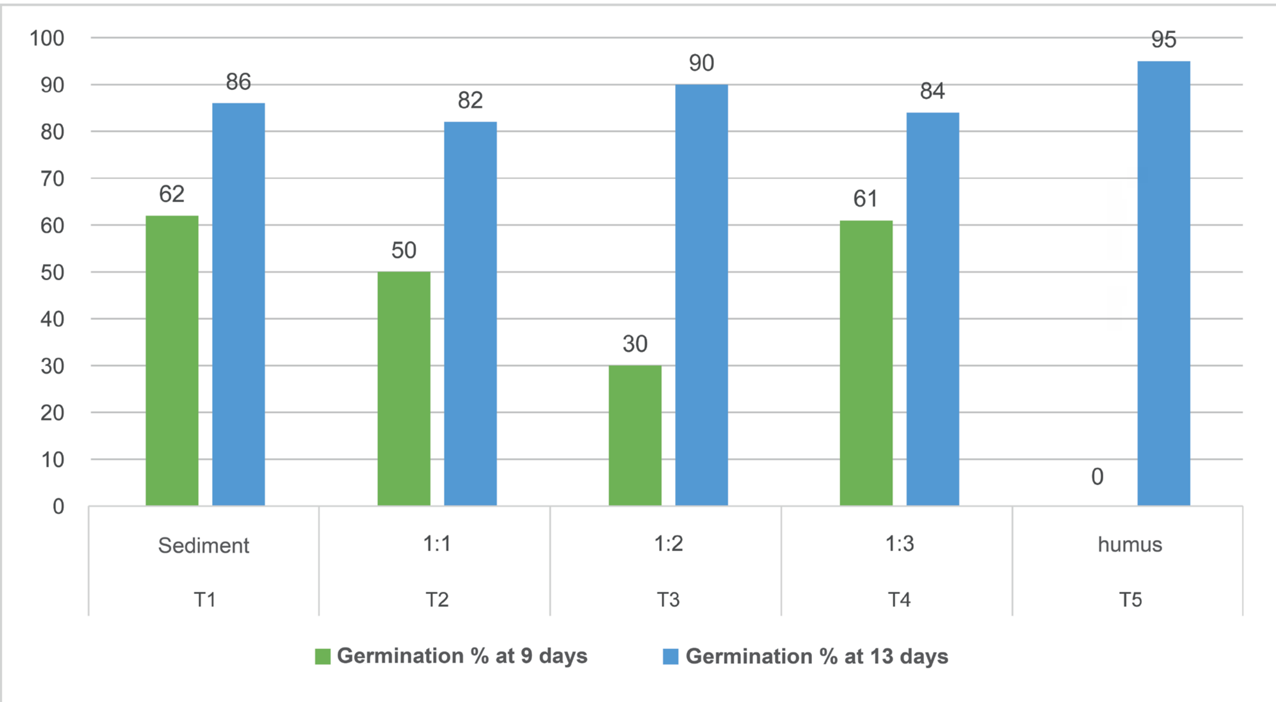

Figure 1. Cumulative germination percentage of seeds of Fine Aroma National Cocoa at 9 and 13 days of post-planting evaluation.

bition necessary to initiate germination (Zahid et al., 2025). From a critical agronomic perspective, this result shows that the chemical richness of the substrate does not guarantee biological success in the initial phenological stages; the porous physical structure and the ionic balance of the medium are equally indispensable conditions. This behavior, attributable to phytotoxicity from excess organic matter and high electrical conductivity, has been reported in organic substrates of high nutritional density (Vences-Martínez et al., 2025), since cacao seeds are highly sensitive to the osmotic potential of the substrate, where an excess of salts or nutrients concentrated in pure humus can block the water imbibition necessary for initial vigor (Wang et al., 2024).

However, when evaluating the germination dynamics at 13 days, a drastic change in the ranking of the treatments was observed, where T5 (100% humus) overcame the initial dormancy to reach the highest success rate with 95%, followed by T3 (1:2 ratio) with 90%.

This productive leap indicates that, once the osmotic barrier is overcome and moisture is stabilized, the high nutrient concentration of the cattle manure and water hyacinth humus enhances development once the active metabolic phase has begun. For their part, T1 and T4 finished with 86% and 84% respectively, showing that, although sediment facilitates rapid early emergence, substrates with a higher organic load consolidate superior germinative vigor over the medium term (Cardoza-Viera et al., 2024). These final results in T2 and T3 confirm that, although humus proportions require more time to reach physical stability, the combination of the cattle manure and water hyacinth biofertilizer with sediment is the most efficient strategy to guarantee an organic productive quality that does not compromise the metabolic development of the crop, which is dependent on environmental and nutritional factors (Cardoza-Viera et al., 2024).

3.2. Average seedling height growth

At 9 days of evaluation, the results show a variation in aerial growth as a function of the composition of the substrate used. T1 recorded the highest growth value with an average of 17.12 cm, and a decreasing growth trend was observed as the proportion of organic load in the mixtures increased, with T2 and T3 obtaining values of 14.87 cm and 14.75 cm, respectively. For its part, T4 reached 10.66 cm, while the minimum growth value was identified in T5 (100% humus control) with only 8.50 cm in height.

The fact that the sediment control treatment (T1) achieved the highest average growth coincides with studies where sandy soils favor early establishment (Buriticá et al., 2025). Conversely, the fact that T5 recorded the lowest growth is due to inhibition attributed to the high electrical conductivity of the cattle manure and water hyacinth humus, which generates osmotic stress that restricts cell growth (Allen et al., 2024). The intermediate treatments T2 and T3 show a decreasing trend as the organic load increases, confirming that an excess of minerals such as K can alter the water potential in FANC (Adet et al., 2024).

The average growth values reached by the FANC seedlings at the fourteenth day of evaluation show the persistence of variations in vegetative development according to the substrate composition. T1 (100% sediment) maintained the highest growth value with an average of 15.6±1.07 cm. This shows that the physical structure of the sediment continues to favor the mechanical expansion of the stem in early stages (Quinde Melo, 2024). In addition, the nutrient reserve content of the cotyledons appears to contribute efficiently in the early stages of germination and growth. Excess nutrients in the substrate can cause an inhibitory effect on germination, whereas mixtures of other substrates with humus at moderate levels favor or normalize germination; furthermore, cacao seeds store nutrients in the cotyledons.

In contrast, the treatments enriched with organic matter presented stabilized values, where T3 recorded 13.8±0.67 cm and T4 reached 13.6±2.08 cm. T2 reported a growth of 11.8±1.18 cm, while the minimum growth value was again identified in T5 (100% humus control), with a record of 11.6±2.19 cm.

Excess humus in the substrate can compromise the porous structure of the soil, reducing the aeration and drainage necessary for cacao root development (Oviedo-Ocaña et al., 2017). This is supported by the optimal aeration of the rhizosphere, which allows a constant flow of oxygen to the roots, a determining factor for the vegetative vigor of FANC (Pineda Pineda et al., 2020). However, stabilization is observed in enriched treatments such as T2, T3, and T4, suggesting that the gradual assimilation of the nutrients supplied by the humus produced begins to balance development relative to the control (Ruiz Flores, 2025). In contrast, the value reached by T5 shows a growth trend similar to T2, T3, and T4. This is possibly due to the reduction of the nutrient content that initially generated an inhibitory effect due to the excess mineral load of the humus, which acted as a limitation on the osmotic potential necessary for sustained cell growth (Jaimes-Suárez et al., 2022). Consequently, the results at 14 days reinforce the need to use balanced organic mixtures to avoid the delay in physiological growth induced by saturated substrates.

3.3. Leaf number

The recorded values of the average number of leaves developed by the FANC seedlings, at the fourteenth day of post-sowing evaluation, show a differentiated response according to the organic load present in the substrate. Regarding T3 (1:2 ratio), a trend emerges in which the nutrient content could initiate stimulation in terms of foliar development, based on leaf number, reaching an average of 4.4. For their part, treatments T2 (1:1) and T4 (1:3) presented identical behavior with an average of 4.2 leaves. Finally, the sediment control (T1) and the pure humus treatment (T5) recorded the minimum values of the evaluation, with an average of 4.0 leaves each.

The measurements corresponding to the leaf development reached by the seedlings at the end of the 27-day period reflect a marked trend toward growth stabilization in the treatments with organic mixtures compared to the sediment control. T1 (Sediment) recorded the greatest foliar development with an average length of 10.5 cm, with a standard deviation in the experiment of 1.48. The treatments with humus mixtures showed similar values to each other: T4 reached 7.5 cm, while treatments T2 and T3 reported a growth of 7.4 cm. The lowest development value was observed in treatment T5 (100% humus), with a record of 6.7 cm.

The differences between treatments are not statistically significant at 14 days, indicating similar foliar development in all treatments during this stage, which coincides with studies where balanced mixtures favor early foliar development ahead of the rest of the treatments (Batista-Sánchez et al., 2024). However, when observing the development of these leaves at 27 days, it is the sediment (T1) that leads; this indicates that, although humus mixtures produce more leaves initially, alluvial sediment allows greater blade expansion and growth due to its porosity and lower mechanical resistance (Avila Pedraza, 2025).

From a chemical standpoint, the high concentration of K (7,306.79 mg kg^{-1}) and P (3,344.00 mg kg^{-1}) in the humus (T5) explains why this substrate, despite having a slow start, manages to match the leaf number of the control by the fourteenth day. The inhibition of germination at day 9 in T5 is attributed to an excess of mineral salts that generates stress, delaying emergence but not limiting the foliar production capacity once the seedling is established (Meza et al., 2007). This behavior is characteristic of organic substrates of high nutritional density, where the subsequent vegetative vigor compensates for the initial dormancy induced by the medium.

The analysis of leaf length at 27 days reveals a divergent physiological response: T1 (Sediment) exceeded the average extension of T5 by 56%. This metric superiority of pure sediment suggests that it allows a maximum expansion of the FANC leaf blade (Mollericona Alfaro et al., 2022). In contrast, in the mixtures with humus, growth appears to be limited by the density of the substrate, which prioritizes the formation of more compact but less extensive tissues (Domínguez et al., 2010).

From the standpoint of mineral balance, the marked difference between the length of T1 and T5 can be explained by the high electrical conductivity that usually accompanies K concentrations above 7,000 mg kg^{-1}. This excess of nutrients in pure humus acts as a limitation for cell growth, since the metabolic effort shifts toward regulating the internal water balance of the *Theobroma cacao* seedlings (Alvarado Zamora y Ramos Remache, 2024). Consequently, the seedling under nutritional stress from excess tends to present leaves of smaller longitudinal dimension, despite possessing a higher chemical reserve in the substrate (Jaume et al., 2023).

Finally, the intermediate mixture proportions (T2, T3, T4) show morphological stability with lengths ranging only between 7.4 and 7.5 cm, evidencing a uniform adaptive response to the presence of organic matter. The T2, T3, and T4 mixtures showed similar values (7.4-7.5 cm), suggesting a uniform response to the presence of organic matter (Amador Sacoto et al., 2022).

3.4. Presence of heavy metals (Pb and Cd)

Table 3 details the Pb and Cd concentrations identified in the substrates after the stabilization process; the results show that Pb levels were higher than Cd levels in all of the treatments evaluated. The highest Pb concentration was recorded in treatment T4, closely followed by T2. This behavior can be linked to the adsorption capacity of the organic matter and the characteristics of the sediment, where the presence of lead in the fluvial sediments of the area can reach detectable levels due to the persistence and bioaccumulation of this metal in riverbeds (Zender Peña et al., 2025).

It is notable that T5 (100% humus) presented the lowest Pb level, suggesting that the stabilization of cattle manure and *Eichhornia crassipes* can contribute to lower lead availability compared to mixtures that include sediment (Zeeshan Manzoor et al., 2024).

On the other hand, Cd levels remained stable below 1.00 mg kg^{-1} in all samples, with a uniform concentration of 0.98 mg kg^{-1} detected in treatments T2, T4, and T5. The stability of these values indicates that

Table 3. Concentration of heavy metals (mg kg-1) in the evaluated treatments.

Treatments	Lead (Pb)	Cadmium (Cd)
T1	2.12	0.00
T2	2.30	0.98
T3	1.48	0.91
T4	2.35	0.98
T5	1.15	0.98

the use of *Eichhornia crassipes* (water hyacinth) as an input is safe, despite its high natural capacity to act as a biomonitor and accumulator of Cd in aquatic ecosystems of the region (Maddock et al., 1988). Treatment T3 (1:2) reported the minimum value of 0.91 mg kg^{-1}, while T1 showed no detectable presence of the metal, which is consistent with previous reports where Cd in certain agricultural soils of Ecuador is found within permissible limits or as a trace element, in accordance with the Soil Technical Standard of Ecuador, based on Ministerial Agreement 097-A (Book VI, Annex 2) of the Ministry of Environment and Energy.

These low levels of Cd contamination in the local inputs of the La Pastora Sol Farm are fundamental, since high concentrations of this metal could disrupt physiological processes and reduce the final productivity of the cacao crop (Chancay Alcívar et al., 2022). Finally, the proper management of these organic residues ensures that the initial metabolic development of FANC is not compromised by phytotoxicity factors.

In agreement with these results, studies carried out on cacao-growing soils of the province of Manabí under conventional management report Pb and Cd concentrations within similar ranges, generally below the maximum permissible limits established by Ecuadorian regulations. This suggests low pressure from metal contamination in local production systems (Navia-Bermello et al., 2025). This coincidence reinforces the idea that the inputs used at the La Pastora Sol Farm present adequate conditions for the establishment and initial development of FANC.

3.5. Analysis of variance and multiple comparisons

The analysis of variance [ANOVA] for growth at day 14 determined highly significant differences among the treatments evaluated ($p < 0.001$) (Table 4). Tukey's test made it possible to identify four significance groups, where T1 (sediment) led growth (Group A), followed by the T3 and T4 mixtures (Group B). Treatment T5 (100% humus) presented the lowest performance, being relegated to Group D.

The convergence of both statistical tests reveals that, although humus is a valuable nutritional contribution, its mineral density, particularly the high K levels recorded, acts as an initial physicochemical limitation. While the ANOVA separates T1 as the best due to its porosity and aeration, the regression precisely quantifies how the excess organic amendment slows the cell turgor necessary for expansion (Luna-Fletes et al., 2025). This negative linear response suggests that FANC prefers a less saturated growth medium during the first two weeks (Amador Sacoto et al., 2022).

On the other hand, the stability of Group B (T3 and T4) in Tukey's test indicates that there is a tolerance range in which the plant can benefit from organic nutrition without drastically sacrificing its vigor (Simonne et al., 2024). Consequently, the use of the 1:2 proportion (T3) is recommended as the optimal management point, since it combines the highest cumulative germination percentage at 13 days (90%) among the organic mixtures, a growth of 13.8 cm at day 14, and the highest number of leaves (4.4). Although T1

Table 4. Tukey growth and clustering results on day 14.

C1 (Treatment)	N	Mean	Grouping			
T1	3	15,6000	A			
T3	3	13,8000		B		
T4	3	13,6000		B		
T2	3	13,2000			C	
T5	3	11,6000				D

(pure sediment) recorded the highest growth in all the variables evaluated, its exclusion as a recommended treatment is justified because it lacks organic nutritional input and is not compatible with the objectives of certifiable organic cacao production. Consequently, T3 balances the decreasing trend of regression with an adequate nutritional base for long-term sustainable development (Torres Castillo et al., 2025).

4. Conclusions

The research demonstrates that the use of humus derived from cattle manure and water hyacinth (*Eichhornia crassipes*) constitutes a viable technical alternative for FANC production, provided that balanced proportions with sediment are managed; therefore, it is concluded that, although humus offers the highest macronutrient content, its direct application inhibits the initial germination period. Consequently, the 1:2 mixture (T3) is the most efficient, presenting the highest cumulative germination among the organic mixtures at 13 days (90%), a competitive growth of 13.8 cm at day 14, and the highest number of leaves (4.4); whereas T1, although superior in initial growth, lacks organic input and is not compatible with organic cacao production certification.

The environmental safety of the humus production protocol is validated by the low presence of heavy metals in the final substrates, which remain significantly below the permissible phytotoxicity limits; thus, the most relevant finding lies in the capacity of the organic mixture to stabilize cadmium at trace levels, guaranteeing that the plant material produced at the La Pastora Sol Farm is suitable for organic certification and export programs. These results establish a scientific basis for the utilization of invasive aquatic biomass, transforming it from an environmental problem into a strategic resource for the sustainable fertilization of cacao cultivation.

Contributor roles

- Ever Darío Morales Avendaño: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.
- Melany Pierina Bravo Cedeño: Investigation, Data curation, Writing – original draft.
- Aldrin Dairy Monero Veliz: Investigation, Resources, Visualization.
- Rodolfo Jeampier Plaza Choez: Software, Formal analysis, Validation.
- María Fernanda Vinces Pin: Writing – review & editing, Validation, Funding acquisition.
- Cesar Xavier Palacios Tapia: Investigation, Writing.
- Manuel Ángel Vélez Sabando: Investigation, Methodology.

Data availability

Data will be available on request.

Use of Artificial Intelligence

The authors declare that Artificial Intelligence was not used in the preparation of this manuscript.

Ethical implications

The authors declare that there are no ethical implications.

Conflict of interest

The authors declare that they have no affiliation with any organization with a direct or indirect financial interest that could have appeared to influence the work reported.

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