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Evaluation of nutrition sources in cacao (*Theobroma cacao* L.) and their impact on yield

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ABSTRACT

Objective. The present study evaluated the effect of three fertilization sources —chemical fertilizer, organic compost, and a no-fertilizer treatment— on yield components of the cacao crop.

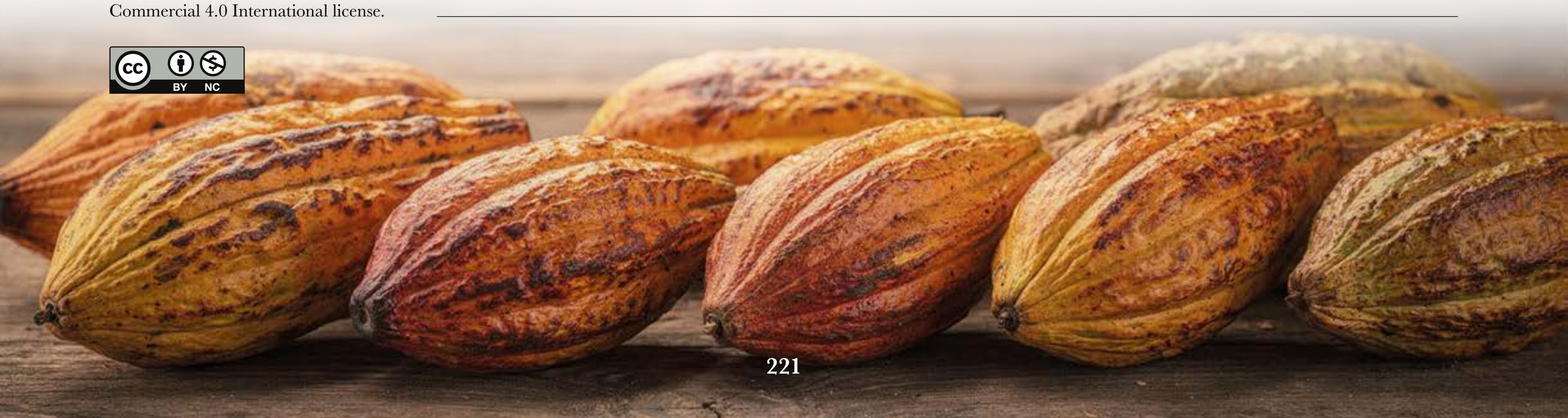
Materials and Methods. The experiment was conducted at the Rosario Izapa Experimental Field of INIFAP in Chiapas, Mexico, where the effect of three nutritional treatments (chemical fertilization, compost, and control) on yield components of six cacao clones (CATIE R4, Regalo de Dios, CAERI 1, CAERI 2, CAERI 4, and SCA12) was evaluated. The experiment was established under a randomized block design with three replications, each replication consisting of three trees per clone. Fruits were harvested from each clone, and variables were measured from 20 fruits per tree.

Results. Organic compost was the most effective nutrient source, showing significant improvements in the number of fruits and dry bean weight. Chemical fertilization showed a limited response, in some cases similar to the control treatment, indicating low efficiency under certain edaphic conditions. The control treatment showed values similar to organic fertilization in the total number of seeds variable.

Limitations/Implications. Cacao nutrition is a closed system in which many factors interact, particularly shade trees that either contribute nutrients or compete for them within the system, and whose effects are sometimes difficult to quantify.

Findings/Conclusions. These findings suggest that the use of compost not only improves cacao productivity but also represents a sustainable strategy that contributes to the agroecological resilience of the production system.

Keywords: chemical fertilization, compost, clones, fruits, dry bean



INTRODUCTION

Cacao (*Theobroma cacao* L.) is a crop of high economic, social, and ecological relevance in tropical regions, particularly in Latin America. Its production is closely linked to agroforestry systems and sustainable cultivation practices that contribute to food security and rural development (Muñoz *et al.*, 2019; Suarez-Venero *et al.*, 2019). In Mexico, cacao is cultivated on approximately 29,000 ha, with an average yield of 590 kg/ha (SIAP, 2025). Over the last three years, cacao prices have undergone a substantial increase in the price per kilogram of dry beans, rising from 60 to more than 200 Mexican pesos per kilogram (ICCO, 2025). This situation has boosted cacao cultivation in Mexico, particularly in tropical regions where agroclimatic conditions are favorable.

In recent decades, chemical fertilization has been widely used to increase agricultural productivity. However, several studies have reported its negative effects on soil health, edaphic biodiversity, and environmental balance (Castillo and Ramírez, 2018; Gómez and Cañizares, 2021). These practices may lead to natural resource degradation and increased dependence on external inputs, limiting the sustainability of production systems. As an alternative, organic fertilization, especially through compost application, has proven effective in improving the physical, chemical, and biological properties of soil, while also enhancing the vegetative development of crops such as cacao (Jiménez *et al.*, 2020). This type of nutrient management can promote more closed nutrient cycles, reduce the use of agrochemicals, and strengthen agroecosystem resilience. In this context, Paredes and Subia (2014) reported that cacao associated with leguminous species and forest trees can capture between 7.1 and 21.9 t ha^{-1} of carbon.

Despite these advances, there is still limited comparative evidence on the impact of different fertilization sources on cacao yield components in agroforestry production systems. In this study, three nutritional treatments were evaluated: chemical fertilization, organic fertilization through compost, and an unfertilized control. The objective was to compare their effect on cacao yield and contribute to the design of more efficient and sustainable agricultural practices.

MATERIALS AND METHODS

The experimental site is located at the Rosario Izapa Experimental Station (CERI, for its acronym in Spanish) of the National Institute for Forestry, Agriculture and Livestock Research (INIFAP, for its acronym in Spanish) in the municipality of Tuxtla Chico, Chiapas, Mexico, at 14° 40’ N latitude and 92°10’ W longitude, at an altitude of 435 m above sea level. The predominant climate in Tuxtla Chico is warm humid with abundant summer rainfall, with a minimum temperature of 24 °C and a maximum of 30 °C, and an annual precipitation ranging from 1,200 to 5,000 mm (INEGI, 2010).

Soils in the region are characterized by their formation from volcanic ash. The soils at CERI have a clay-sandy texture and belong to the Andosol group, with an approximate depth of 1.5-2 m. The soil has a pH of 6.5 and an organic matter content of 3%.

Plant Material

The cacao clones used in this study were selected based on their tolerance to moniliasis (*Moniliophthora roreri*) (Avendaño *et al*., 2018; Avendaño *et al*., 2019; Phillips-Mora *et al*., 2012) Table 1, Figure 1).

Treatments

Prior to the establishment of the treatments, soil samples were collected from the experimental field where the study was conducted. The samples were analyzed in the laboratory to determine their nutrient composition, and the results are presented in Table 2.

Three treatments were considered in the study: chemical fertilization, organic fertilization, and a control treatment.

Table 1. Cacao clones used for evaluation under different nutritional treatments.

ID	Clon	Response to moniliasis
C1	CATIE R4	Tolerant
C2	Regalo de Dios	Tolerant
C3	CAERI 1	Tolerant
C4	CAERI 2	Tolerant
C5	CAERI 4	Tolerant
C6	SCA 12	Susceptible

Figure 1. Genotipos de *Theobroma cacao* L. CAERI-1 (a), CAERI-2 (b), CAERI-4 (c), CATIE-R4 (d), SCA-12 (e), Regalo de Dios (f).

Table 2. Soil characteristics of the experimental site.

M	pH	OM (%)	N_NO_3 (ppm)	N (kg/ha)	P (kg/ha)	K (kg/ha)	Ca (ppm)
1	6.37	8.73	15.37	305.5	4.9	192.2	1166
2	6.35	8.64	14.69	302.4	3.1	129.7	1163
3	6.27	8.90	14.41	311.4	3.6	139.8	1334
4	6.27	9.00	12.63	315.1	4.5	136.3	1373

Table 2. Continued…

M	pH	OM (%)	N_NO_3 (ppm)	N (kg/ha)	P (kg/ha)	K (kg/ha)	Ca (ppm)
1	114.35	10.30	28.48	2.68	3.10	1.044	0.102
2	108.88	5.89	29.41	2.71	2.91	1.027	0.103
3	127.07	7.36	26.66	2.63	4.68	1.096	0.098
4	124.08	1.47	25.86	2.70	4.65	1.04	0.103

M=Samples.

Chemical fertilization: Chemical fertilizer was applied starting six months after the establishment of cacao plants at a dose of 150 g per plant. The chemical composition of the fertilizer used is presented in Table 3. The fertilizer was applied manually in a circular band around the plant (50 cm from the stem) using a hoe and then covered with soil. Fertilization was carried out every 90 days until the productive stage of the plants.

Organic fertilization: The treatment was applied starting six months after the establishment of cacao plants at a dose of 1.5 kg of compost per plant. The chemical composition of the compost is presented in Table 4. The application was carried out manually, following the same procedure as chemical fertilization, with application intervals every 90 days until the productive stage of the plants.

Agronomic Management

For agronomic management, the plots were established with temporary shade (*Cajanus cajan*) and permanent shade (*Gliricidia sepium*). Cacao plants were established at a spacing of 3 m between plants and 3 m between rows. Weed control was carried out manually using a machete. Formative pruning was performed during the first six months

Table 3. Chemical composition of the fertilizer used in the experiment.

Component	Amount (%)
N-Total	21.0
N-Nitric	10.0
N-Ammoniacal	11.0
Phosphorus P_2O_5	17.0
Potassium K_2O	3.0
Sulfur	4.0
Zinc	0.15
Magnesium MgO	0.4

Table 4. Nutrient composition of the compost.

Component	Amount
pH	7-8
C.E ds/m	4-10
Organic matter (%)	12-30
Total nitrogen (%)	1.2-2.5
Phosphorus P_2O_5 (%)	0.5-2
Potassium K_2O (%)	0.53
Calcium CaO (%)	2-4
Magnesium MgO (%)	0.5-0.8
Sodium (%)	0.2
Sulfur (%)	0.2-0.45
Manganese (ppm)	550
Iron (ppm)	5000
Zinc (ppm)	150
Copper (ppm)	33
CEC Meq/100 g of soil	80-300

CE=Electrical conductivity, CEC=Cation exchange capacity. Control treatment. No type of soil fertilization or nutrient input was applied.

after plant establishment, followed by maintenance and fruiting pruning. For pest and disease management, diseased fruits were removed, pruning was conducted, and copper oxychloride was applied at a dose of 3 gL^{-1} of water three times per year. Harvesting was carried out manually.

Experimental designand evaluated variables

A randomized block design with three replications was used, with each replication consisting of three trees per clone. Once the plants reached the productive stage, 20 fruits were harvested from each clone and taken to the laboratory for evaluation. Variables related to yield components were evaluated, including pod index (number of pods required to obtain 1 kg of dry beans), Pod length (PL, cm), Pod width (PW, cm), fruit exocarp thickness (FET, mm), total number of seeds (TNS), total fresh seed weight (TFSW, g), fruit weight (FWt, g), total dry seed weight (TDSW, g), and individual dry seed weight (IDSW, g). Dry seed weight was determined at 7% moisture content. Data collection was carried out twice per year (in each harvest cycle) for two consecutive years.

Statistical Analysis

An analysis of variance (ANOVA) was performed according to the randomized block experimental design model, followed by a mean comparison using Tukey's test at α=0.05.

RESULTS AND DISCUSSION

Fruit Variables

According to the analysis of variance, no statistical differences were found for the source of variation "clones" in the variables TNS and FWt, while the remaining variables showed highly significant differences. For the source of variation "nutrition," highly significant differences were found only in the pod index (PI). Finally, for the clone × nutrition interaction, a statistically significant difference was found only in fruit exocarp thickness (FET) (Table 5).

When comparing means among clones, regardless of the treatment applied, the CATIE R4 clone (C1) showed the lowest PI (25.9 pods), whereas the SCA12 clone (C6) showed the highest PI (40.1 pods). The CAERI 1 clone (C3) presented the highest PL (20.5 cm), while the lowest PL was observed in the SCA12 clone (C6, 15 cm). The CAERI 4 clone (C5) showed the highest PW (9.06 cm), whereas the lowest PW was recorded in the SCA12 clone (C6, 6.86 cm). CAERI 1 (C3) exhibited the highest FET (15.8 mm), while the lowest value was observed in SCA12 (C6, 10.3 mm) (Table 6).

In the variable total number of seeds, the clone CAERI 2 (C4) showed the highest number of seeds (37.6), while Regalo de Dios (C2) had the lowest number of seeds (27.9). However, in relation to total fresh seed weight, the clone CATIE R4 (C1) obtained the highest weight (142 g), whereas the lowest weight was recorded in the clone SCA12 (C6, 77.1 g). Finally, for the fruit weight variable, the clone CAERI 4 (C5) showed the highest average fruit weight (615.1 g), while the lowest fruit weight was obtained from the clone SCA12 (315.4 g) (Table 7).

Table 5. Sum of squares from the analysis of variance for fruit variables.

SV	DF	PI	PL	PW	FET	NTS	TFSW	FW
Clon	5	5069**	333.7 **	58.3 **	413.4 **	371.8 ns	59699**	139501ns
Nut	2	377.6*	10.3 ns	1.2 ns	10.3 ns	259.5 ns	50034 ns	55368 ns
Clon*Nut	10	48.2 ns	76.2 ns	11.1 ns	90.9 *	938.7 ns	8567 ns	246662ns

SV=source of variation; Nut=nutrition; DF=degrees of freedom; PI=pod index; PL=pod length; PW=pod width; FET=fruit exocarp thickness; TNS=total number of seeds; TFSW=total fresh seed weight; FW=fruit weight.

Table 6. Mean comparison of PI, PL, PW, and FET variables.

PI			PI			PL			FET		
Clon	Mean	Tuk	Clon	Mean	Tuk	Clon	Mean	Tuk	Clon	Mean	Tuk
6	40.1	a	3	20.5	a	5	9.06	a	3	15.8	a
2	31.9	b	2	19.8	a	3	8.53	b	2	15.3	a
4	29.1	b	1	18.3	b	1	8.55	b	1	15.0	a
5	26.7	b	5	17.5	b	4	8.25	b	5	14.6	a
3	26.4	b	4	17.3	b	2	8.16	b	4	14.5	a
1	25.9	b	6	15	c	6	6.86	c	6	10.3	b

Mean=Mean value, Group=Statistical group, PI=pod index; PL=pod length; PW=pod width; FET=fruit exocarp thickness; Tuk=Tukey's aggrupation.

Table 7. Mean comparison of TNS, TFSW, and FW variables among cacao clones.

TNS			TFSW			FW		
Genotype (Clon)	Mean	Tuk	Genotype (Clon)	Mean	Tuk	Genotype (Clon)	Mean	Tuk
4	37.6	a	1	142.0	a	5	615.1	a
3	35.1	a	5	141.2	a	3	613.1	a
5	34.3	ab	3	125.6	ab	1	595.2	a
1	32.3	ab	4	113.6	bc	2	571.9	ab
6	31.8	ab	2	94.5	c	4	496.5	b
2	27.9	b	6	77.1	d	6	315.4	c

Mean=Mean value, Group=Group, TNS=Total number of seeds; TFSW=Total fresh seed weight; FW=Fruit weight; Tuk=Tukey's aggrupation.

When analyzing fruit variables according to the type of nutrition, it was observed that plants treated with compost and control plants had the lowest PI, while chemical fertilization required more pods to produce one kilogram of dry beans. The use of compost also had an effect on PL, PW, and FET, where the highest values were obtained. For TNS, no statistical differences were observed among fertilization types; however, the use of compost showed a higher number of total seeds (Figure 2). The effect of compost use was also reflected in TFSW and FW, presenting heavier fruits and a higher number of total seeds (Figure 3).

Seed variables

According to the analysis of variance for seed variables, highly significant statistical differences were observed among clones for all analyzed variables. For the source of variation type of nutrition, no significant statistical differences were observed only in ST (seed thickness), while the remaining variables showed highly significant statistical differences. For the clone × nutrition interaction, highly significant statistical differences were observed for all variables (Table 8).

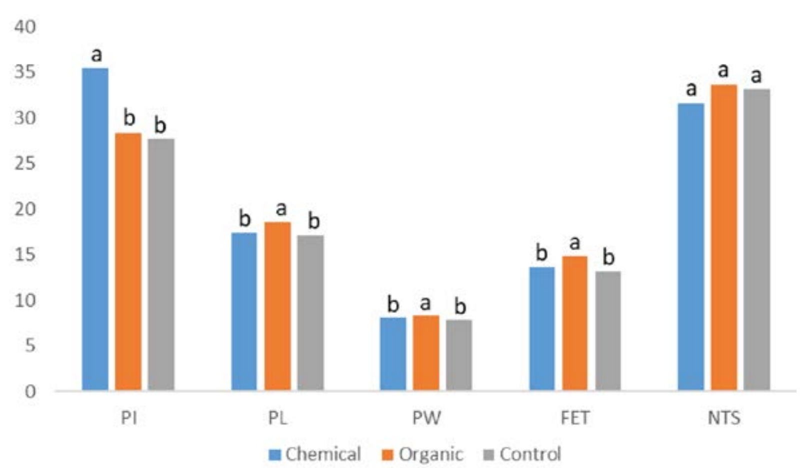


Figure 2. Mean comparison of variables. PI=pod index; PL=pod length; PW=pod width; FET=fruit exocarp thickness; TNS=total number of seeds.

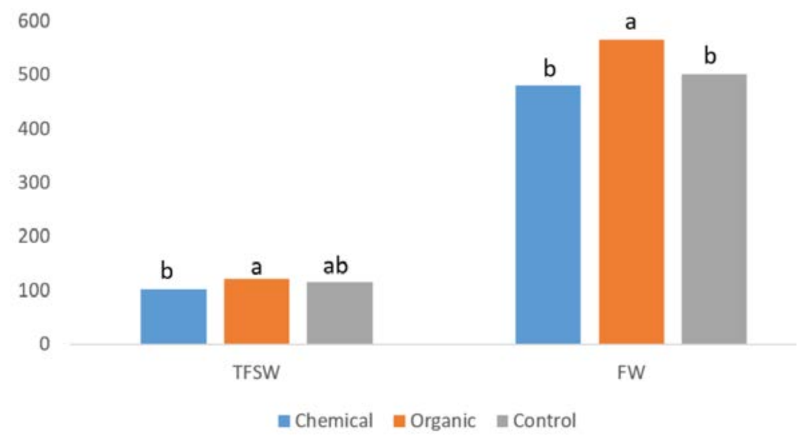


Figure 3. Mean comparison of TFSW and FW under three types of nutrition in cacao.

Table 8. Sum of squares of the analysis of variance for seed variables.

SV	DF	SL	SW	ST	FSWI	SI
Clon	5	2900.7 **	1272.8 **	850.6 **	338.6 **	46.1 **
Nut	2	146.3 **	17.6 **	1.2 ns	3.4 **	0.4 **
Clon*Nut	10	340.7 **	76.0 **	45.7 **	20.3 **	2.6 **

SV=source of variation; Nut=nutrition; DF=degrees of freedom; SL=seed length; SW=seed width; ST=seed thickness; FSWI=fresh seed weight per individual seed; SI=seed index.

When performing the mean comparison among clones, CATIE R4 (C1) showed the highest seed length (24.6 mm), while SCA12 (C6) showed the lowest seed length (19.7 mm); for ST, SW, and IS, CATIE R4 (C1) showed the highest values, with 12.6 mm, 9.4 mm, and 1.2 g, respectively, whereas SCA12 (C6) showed the lowest values of 9.5 mm, 6.5 mm, and 0.7 g, respectively (Table 9).

When analyzing the mean comparison among types of nutrition and their effect on seed variables, organic fertilization based on compost showed the highest values for SL, SW, ST, and SI, while chemical fertilization showed the lowest values for SL, SW, and SI (Figure 4).

Table 9. Mean comparison of seed variables SL, SW, GS, and SI among six cacao clones.

SL			SW			ST			SI		
Genotype (Clon)	Mean	Tuk	Genotype (Clon)	Mean	Tuk	Genotype (Clon)	Mean	Tuk	Genotype (Clon)	Mean	Tuk
1	24.6	a	1	12.6	a	1	9.4	a	1	1.2	a
5	23.4	b	5	12.1	b	2	9.3	a	5	1.1	b
4	22.9	c	3	11.9	c	3	8.9	b	2	1.1	bc
3	22.7	c	4	11.9	c	4	8.3	c	3	1.1	c
2	22.2	d	2	11.8	c	5	8.2	c	4	1.0	d
6	19.7	e	6	9.5	d	6	6.9	d	6	0.7	e

Mean=mean value; Group=statistical group; SL=seed length; SW=seed width; ST=seed thickness; SI=seed index; Tuk=Tukey's aggrupation.

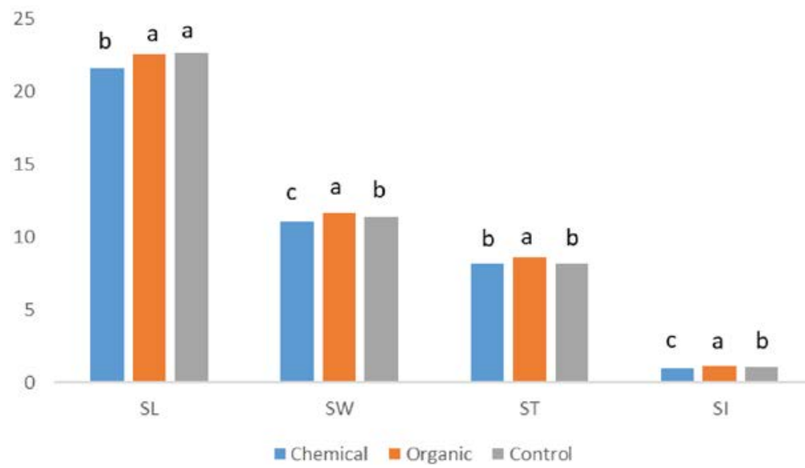


Figure 4. Mean comparison analysis of seed variables in cacao under three types of nutrition (SL=seed length, SW=seed width, ST=seed thickness, SI=seed index).

The data obtained in this study show that organic nutrition was the most effective source of nutrition in terms of cacao yield. This advantage can be attributed to its capacity to improve soil structure, promote microbiological activity, and release nutrients progressively. Studies such as Jiménez *et al.* (2020) indicate that the incorporation of organic residues significantly improves the vegetative and reproductive development of cacao, especially in soils with low initial fertility. Similarly, Mulia *et al.* (2017) demonstrate that under marginal and acidic soil conditions, organic amendments, particularly compost, have a significantly greater impact on cacao growth and productivity than mineral sources applied in isolation. Plants treated with compost showed greater height, higher flowering, and up to five times higher dry bean yield than treatments based exclusively on mineral fertilization.

Although chemical fertilizer provides rapidly available nutrients, in this study its performance was lower than that of organic nutrition. Previous research has found that synthetic inputs may have a transient effect on productivity and, in some cases, low efficiency depending on soil type (Castillo and Ramírez, 2018). This suggests that cacao may respond more favorably to organic sources when sustainability and resilience in cultivation are sought. The unfertilized treatment (control) showed the lowest yield, highlighting the need to implement plant nutrition practices to achieve economically viable production. According to Díaz *et al.* (2017), cacao cultivated without any type of fertilization produces a lower number of fruits per plant and lower dry seed weight, limiting its commercial potential.

Beyond yield, the use of compost as a source of organic nutrition represents a sustainable alternative that utilizes local organic residues and promotes a circular approach in agriculture. Authors such as Gómez and Cañizares (2021) state that agricultural systems integrating organic fertilizers improve soil biodiversity and contribute to climate change mitigation. In addition, several studies conducted in Mexico, Colombia, Ecuador, and other countries (Francisco-Santiago *et al.*, 2023; Vega *et al.*, 2021; Castillo-Garrido, 2024; Schmidt *et al.*, 2024) agree that the application of organic fertilizers, compost, and biofertilizers in cacao cultivation increases the number of fruits and yield per plant, improves soil fertility and microbial activity, enhances productive stability and bean quality, and reduces dependence on chemical inputs, promoting more resilient agricultural systems.

Dogbatse *et al.* (2021), based on their results, conclude that inorganic fertilization is more effective in promoting rapid growth during the early stages of cacao; however, organic fertilization improves soil health and favors stronger root development. Therefore, they recommend an integrated strategy (organic + inorganic), as it combines vigorous growth, improved nutrient absorption, and soil sustainability. In this regard, Leiva-Rojas (2022) also states that the integration of organic and mineral sources is a recommended strategy, since cacao nutrition is a dynamic process dependent on the phenological stage, and nutrient uptake is closely linked to cacao physiology, while genetic and environmental variability conditions the response to fertilization. Similarly, López-Baez *et al.* (2015) highlight that cacao responds better to balanced and gradual nutrition than to intensive fertilizer applications. However, Marrocos *et al.* (2020) report that adequate mineral nutrition is a determining factor for productive sustainability, reflected in yield, physiological efficiency, and crop resilience. Sánchez *et al.* (2005) support the importance of implementing mineral fertilization programs in cacao systems where nutrition is limited, and Uribe *et al.* (2008) report that balanced mineral fertilization is a key tool to improve cacao productivity and can help overcome low yields.

CONCLUSIONS

Organic fertilization (compost) proved to be the most efficient source of nutrition, significantly improving cacao yield compared to chemical fertilizer and the unfertilized control. Chemical nutrition showed variable results, with a lower response compared to organic nutrition, suggesting that its use should be considered with caution depending on cacao clone, soil type, and agricultural management. On the other hand, the unfertilized treatment confirmed the need for effective nutrient management practices to achieve viable production.

Finally, organic fertilization (compost) offers additional benefits, such as improved soil structure, enhanced soil biological activity, and reduced environmental impact. This study provides valuable evidence to support the transition toward more sustainable agricultural production models in high-value tropical crops such as cacao under agroforestry systems.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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