Leaf litter production and potential nutrient return in agroforestry systems with cacao and tropical fine woods †

[Producción de hojarasca y retorno potencial de nutrientes en sistemas agroforestales con cacao y maderas finas tropicales]

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SUMMARY

Background: Leaf litter production in agroforestry systems represents a potential return of nutrients to the soil through decomposition and mineralization processes. **Objective:** To evaluate the nutritional contribution of leaf litter produced in an agroforestry system (AFS) of cacao (*Theobroma cacao* L.) variety TCS 19 with tropical fine woods. **Methodology:** An evaluation was carried out in two locations in eastern Colombia (Muzo, Boyacá and Rionegro, Santander); the associated timber species were abarco (*Cariniana pyriformis* Miers) and teak (*Tectona grandis L. f.*) in two planting models (barriers in single rows and double rows). The leaf litter production of individual timber species and their combinations with cacao, as well as the contribution of nutrients (macro- and micronutrients), were evaluated under a randomised complete block design with eight combinations (four species combinations in two planting systems). **Results:** A correlation was found between climatic variables, such as rainfall, and litterfall production, with litterfall production being higher during periods of lower rainfall at both sites. The highest leaf litter production was in treatment TCS 19 cacao with double rows of abarco shading, at 4,248.6 kg ha^{-1} year^{-1} in Muzo, and the least litter production was in single rows of teak, at 343 kg ha^{-1} year^{-1} in Rionegro. For macronutrient supply, the best treatment in Muzo, with the highest contribution, was the TCS 19 cacao with abarco double-rows treatment, which provided nutrients N (56 kg ha^{-1}) and Ca (51 kg ha^{-1}). In Rionegro, the highest contribution was made by the abarco double-rows treatment for the nutrients N (30 kg ha^{-1}) and treatment TCS 19 cacao with double-rows abarco in Ca (34 kg ha^{-1}). **Implications:** The tropical hardwood agroforestry system, featuring cacao, whether planted in single or double rows, provides significant nutritional value due to the litter produced during its physiological and productive development. **Conclusions:** The associated timber species make a differential contribution to litter and the nutrient contents by location. The abarco is the forest species that generates the most significant nutritional contribution through the decomposition of leaf litter in the soil.

Key words: Agroforestry systems; leaf litter; nutrient cycling.

RESUMEN

Antecedentes: La producción de hojarasca en sistemas agroforestales representa un potencial retorno de nutrientes al suelo a través de procesos de descomposición y mineralización. **Objetivo:** Evaluar el aporte nutricional de la hojarasca producida en un Sistema agroforestal (SAF) de cacao (*Theobroma cacao* L.) variedad TCS 19 con maderas finas tropicales. **Metodología:** Se realizó una evaluación en dos localidades del oriente colombiano (Muzo, Boyacá y Rionegro, Santander); las especies maderables asociadas fueron abarco (*Cariniana pyriformis* Miers) y teca (*Tectona grandis L. f.*) en dos modelos de siembra (barreras en las hileras sencillas e hileras dobles). La producción de hojarasca

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de las especies maderables individuales y sus combinaciones con cacao, y el aporte de nutrientes (macro y micronutrientes) se evaluaron bajo un diseño de bloques completos al azar con ocho combinaciones (cuatro combinaciones de especies en dos sistemas de siembra). **Resultados:** Se encontró una correlación entre variables climáticas como la precipitación y la producción de hojarasca; la producción de hojarasca fue mayor durante periodos de menor precipitación en ambos sitios. La mayor producción de hojarasca se presentó en el tratamiento TCS 19 cacao con sombrío de abarco doble hilera con 4,248.6 kg ha^{-1} año^{-1} en Muzo y la menor producción de hojarasca fue teca en hilera sencilla con 343 kg ha^{-1} año^{-1} en Rionegro. Para el aporte de macronutrientes, el mejor tratamiento en Muzo fue abarco en doble hilera con N (56.1 kg ha^{-1}) y Ca (51 kg ha^{-1}). En Rionegro, el mayor aporte lo realizó el tratamiento TCS 19 cacao con abarco para los nutrientes N (30.3 kg ha^{-1}) y Ca (34.3 kg ha^{-1}). **Implicaciones**: El sistema agroforestal de madera dura tropical, que incluye el cacao, ya sea plantado en hileras simples o dobles, proporciona un valor nutricional significativo debido a la hojarasca producida durante su desarrollo fisiológico y productivo. **Conclusiones:** La especie maderable asociada hace un aporte diferencial en la hojarasca y el contenido de nutrientes según la localidad. El abarco es la especie forestal que genera el mayor aporte nutricional por la descomposición de la hojarasca en el suelo.

Palabras clave: Sistemas agroforestales; hojarasca; ciclaje de nutrientes.

INTRODUCTION

Cacao production worldwide is concentrated in three tropical regions, which are significant in terms of production: Africa, Latin America, and Asia. Latin America accounted for 19 % of world production in 2022, equivalent to 825,000 t (International Cocoa Organization, 2022). In Colombia, a large part of the cacao is planted under agroforestry systems, around 90 % of the 196,000 ha of cacao plantations (Jaimes *et al.*, 2021); these systems promote functional processes between plants and microorganisms present in the soil, which leads to an increase in productive, environmental, economic, and social benefits due to their easy adaptation to the environment (Carvalho *et al.*, 2023).

Agroforestry systems with cacao represent a sustainable and productive alternative that enhances productivity (Mena-Mosquera and Andrade, 2021). Cacao requires shade during all stages of development, with the shade requirement decreasing as the crop matures (Carvalho *et al.*, 2023). The association of cacao with other species, such as fruit trees, timber trees, and musaceas, has multiple economic and biological benefits to the system. In the case of timber species, in addition to being a source of timber, food, firewood, and a carbon sink, they contribute to the conservation of soil fertility, reduction of erosion due to the accumulation of organic matter, nitrogen fixation, and nutrient cycling (Chinchilla-Mora *et al.*, 2021; Rangel and Silva, 2020; Rojas and Sacristán, 2013).

In a Cacao agroforestry system (CAFS), the species associated with the main crop generate a nutritional contribution of elements to the soil through the decomposition of leaf litter, which represents an essential stage in the conservation, recycling and acquisition of nutrients (Asigbaase *et al.*, 2021; Rolando and Vides, 2020). The nutrients that are recycled through the litter provided by cacao and associated shade trees (timber and fruit trees) are important in the biogeochemical cycles within the cacao production systems; for this reason, in many cacao plantations, the recycling of nutrients through the decomposition of the litter is crucial for maintaining fertility in the system (Bai *et al.*, 2022). Likewise, leaf litter minimises soil erosion by protecting the soil from the impact of rain, reducing the speed of runoff, and decreasing nutrient loss (Zavala *et al.*, 2018). In its accumulation and decomposition process, biomass contributes the necessary macro and microelements that comprise organic matter. This incorporation promotes the formation of humic substances that contribute to the quality and fertility of the soil (Paz, 2020).

Among the species used in CAFS, abarco (*Cariniana pyriformis* Miers) is a native Colombian species, which is established in association with cacao or in monoculture (Jaimes *et al.*, 2021; Carvalho *et al.*, 2023) and is characterised by its durability, early development, resistance to insect pests and diseases, and high commercial value. These characteristics give it a fundamental economic role due to its multiple uses, malleability, and importance in forestry (Escobar *et al.,* 2023). However, due to massive exploitation, natural populations have been reduced, and it is widely used in reforestation programs (Grajales-Amorocho *et al.,* 2023). On the other hand, teak (*Tectona grandis* L.f.) is a fast-growing species that is resistant to degradation by fungi, termites, and other insects, and is easy to manage without special requirements. For this reason, it is widely used in reforestation projects, particularly in agroforestry systems, due to its versatility (Monsalve-Paredes and Bello-Alarcón, 2020; Shukla and Viswanath, 2023).

In CAFS, the primary sources of litter are cacao and shade trees, which regulate the amount provided depending on the selected trees, density, and canopy cover (Asigbaase *et al.*, 2021). Leaf litter is the major component of litterfall material in agroforestry systems, comprising more than 60% of the total annual litterfall. However, inputs from the shade tree component can improve litter quality and enhance nutrient cycling in these systems (Fontes *et al.*, 2014). Given the importance of shade trees in the fertility of agroforestry systems with cacao, the objective of this research was to evaluate the contribution of leaf litter to the nutrition and nutrient cycling of two planting models and two timber species: Abarco (*C. piryformis* Miers) and Teak (*T. grandis*).

METHODOLOGY

Location and experimental design

The study was carried out in two sites: 1. The La Suiza Research Center of the Colombian Agricultural Research Corporation – AGROSAVIA, located in the municipality of Rionegro, department of Santander at 07°22'12.5" N 73° 10'49.6" W (Figure 1). The elevation of the plot is 500 m above sea level (m.a.s.l.), with a mean annual temperature of 25 °C and a mean annual relative humidity of 80%. The rainfall regime is bimodal, characterised by two distinct dry seasons and two wet seasons. The mean annual rainfall is greater than 2,000 mm (meteorological station at La Suiza Research Center) and 2. Research farm in the Municipality of Muzo, in the department of Boyacá at 05°32'26.7" N 74° 05'48.1" W (Figure 1). The elevation of the plot is 815 m above sea level (m.a.s.l.), with a mean annual temperature of 27 °C and a mean annual relative humidity of 62%. The mean annual rainfall is 2,322 mm (Instituto de Hidrología, Meteorología y Estudios Ambientales [IDEAM], 2021). To establish the effect on leaf litter production in the CAFS according to the planted species, TCS 19 cacao variety was evaluated as the main crop with shade from abarco (*C. pyriformis* Miers) and teak (*T. grandis* L. f.) in single and double row sowing designs. A randomised complete block experimental design was employed, with repeated measures over time, three replications, and two sites. Eight combinations of arrangements or sources of litter contribution were evaluated, as presented in Table 1.

The timber species were established four months before cacao, with planting distances as follows: teak and abarco at a planting distance of 4x4 m, with a density of 50 trees per experimental plot (200 trees per hectare) in single-rows and 75 trees per experimental plot (300 trees per hectare) in double-rows per each timber species; cacao at 3x3 m and a density of 225 trees per experimental plot (900 trees per hectare).

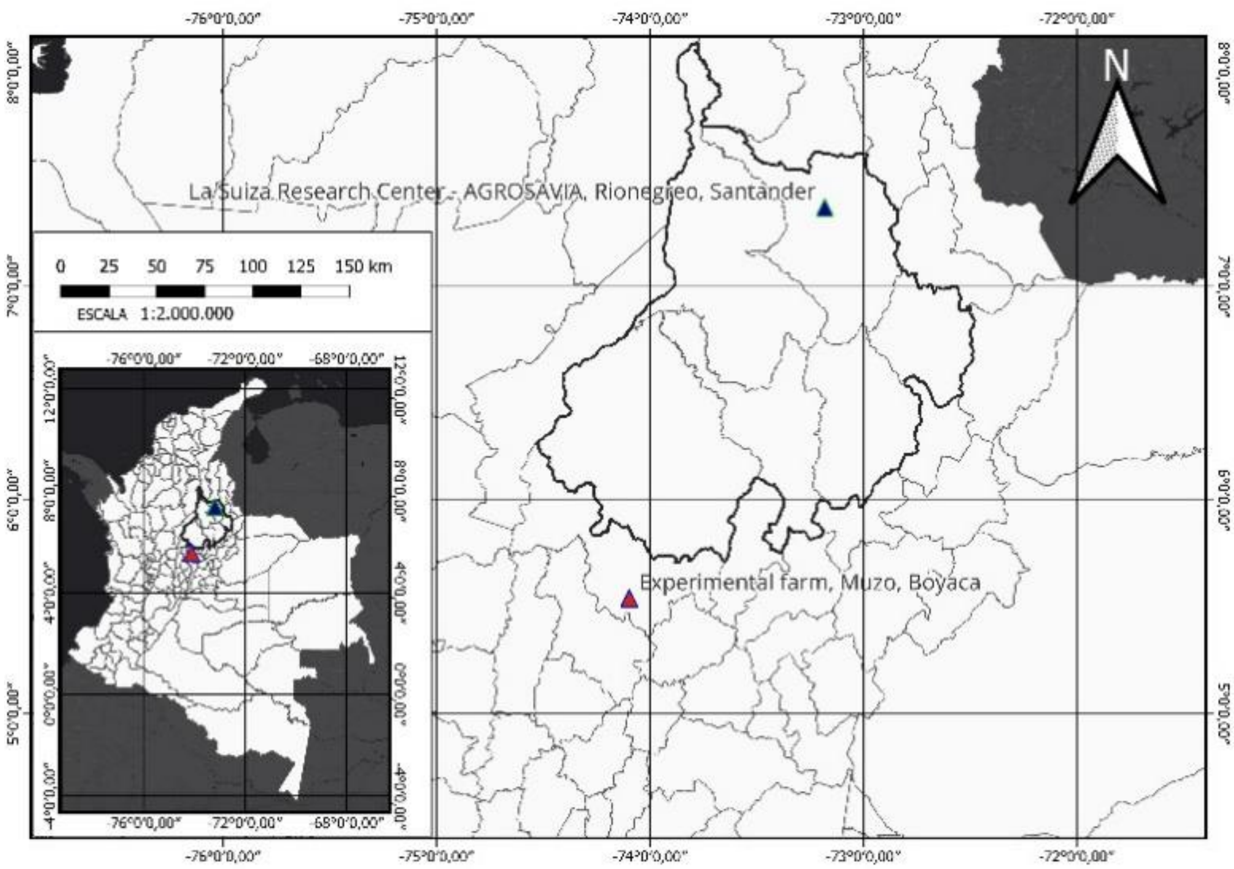

Figure 1. Map showing the locations of the study sites. Source: own elaboration.

Table 1. Description of eight agroforestry treatments based on species composition (monoculture vs. mixed systems) and shade tree planting design evaluated for leaf litter production:

Treatment	Species composition	Planting design
TE_S	Teak only	Single-row
TE_D	Teak only	Double-row
CM_S	Abarco only	Single-row
CM_D	Abarco only	Double-row
CT_S	TCS 19 cacao with teak	Single-row
CT_D	TCS 19 cacao teak	Double-row
CCM_S	TCS 19 cacao with abarco	Single-row
CCM_D	TCS 19 cacao with abarco	Double-row

Note: Single-row (S) and double-row (D) designs refer only to the arrangement of shade trees (teak or abarco). All cacao was planted in a standard arrangement at 3×3 m spacing.

The evaluations were carried out 9 years after planting, during the phenological stage associated with peak cacao production and development. To quantify leaf litter production and its nutritional contribution under eight treatments in two locations, all plant material produced was collected monthly for six months using modified leaf litter traps with areas of 4 m² installed 1.5 m above the ground for timber trees and 0.5 m for cacao trees. Three traps were randomly distributed per treatment, totalling 24 for the entire experiment. (Figure 2).

The leaf litter was collected monthly and taken to the plant analysis laboratory at the La Suiza Research Center for analysis, where the leaves were identified and classified by species. The fresh weight was determined using an analytical balance (Vibra Model AJ 6200E). Initially, the fresh weight was quantified. The samples were then stored in sterile paper bags, duly labelled, to begin the dehydration process. This process was conducted for 72 hours at a temperature of 70°C in muffle ovens, after which the dry weight was recorded. Nutrient quantification was carried out in the analytical chemistry laboratory of AGROSAVIA and the content of total nitrogen, total phosphorus, potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), sodium (Na), iron (Fe), copper (Cu), manganese (Mn), zinc (Zn) and boron (B) were determined using plasma emission spectrometry and atomic absorption spectrometry methodologies.

Figure 2. Modified leaf litter trap with mesh collection surface installed in the cacao understory for monthly quantification of litterfall biomass and nutrient cycling. [Photograph by Eliana Báez].

Statistical analysis

To determine the effect of the interaction between location, species, row type, and measurement period on the fresh and dry weight of the litter, a combined analysis of variance with repeated measures over time was carried out. The first-order autoregressive-heterogeneous correction was applied, followed by Tukey's multiple comparison test. To assess differences in nutrient contribution between locations, a t-test was performed on the potential values from each treatment. Finally, a principal component analysis was employed to identify key components using the Kaiser-Guttman criterion (i.e., eigenvalues greater than 1.0) (Jackson, 1993), and to determine the relationships between treatments and nutrient contents. All analyses were performed using Infostat statistical software (Di Rienzo *et al.,* 2013).

RESULTS

Biomass production, quantified as dry matter (DM) from leaf litter collected in each treatment, showed statistically significant differences for the four-way interaction of study site x species x row type x measurement date (harvest month) ($P< 0.0001$). The highest mean biomass values during the evaluation months were presented in Muzo for CM_D and CM_S (Figure 3), compared to the other treatments evaluated. Similar behaviour occurred in Rionegro, where the highest amount of biomass was presented for CM_D. In general, CM_S and CM_D presented the highest values in leaf litter quantification. In contrast, the lowest leaf litter production was observed in CT_S at both study sites.

The average monthly litter estimated production in kg ha^{-1} year^{-1} (Equation 1) has the highest contribution occurring in the Muzo locality compared to Rionegro (Table 2). The treatment with the highest production is CCM_D (4,249 kg ha^{-1} year^{-1}), followed by CM_D (3,279 kg ha^{-1} year^{-1}). The treatments presented with the lowest values were TE_S (574 kg ha^{-1} year^{-1}) and TE_D (2,253 kg ha^{-1} year^{-1}).

$$HT = \frac{\text{AvgM} \times \text{NumA} \times 12}{1000} \quad \text{(Equation 1)}$$

Where:
HT: Estimated litter production per hectare
AvgM: Average litter per monthly treatment
NumA: Number of trees per hectare (300 in double-rows and 200 in single-rows).

At the Rionegro study site, it was estimated that CM_D could generate the most significant litter contribution (2,484 kg ha^{-1} year^{-1}), followed by CCM_D (1,730 kg ha^{-1} year^{-1}). The treatment with the lowest estimated contribution was TE_S (343 kg ha^{-1} year^{-1}) (Table 2). It was expected that, due to the greater number of cacao trees compared to the shady trees, the accumulation of leaf litter in cacao treatments would be more substantial in both locations. However, this behaviour was not evident in the Rionegro site.

In both sites, the highest litter contribution occurred on February 2,205.91 g in Muzo and 1,456.83 g in Rionegro (Figures 4 and 5). CM_S and CM_D in both study sites produced an average of 4,291.33 g. TE_S, TE_D, CT_S, CT_D, CCM_S, and CCM_D did not produce more than 1,626 g on average during the six-month evaluation period.

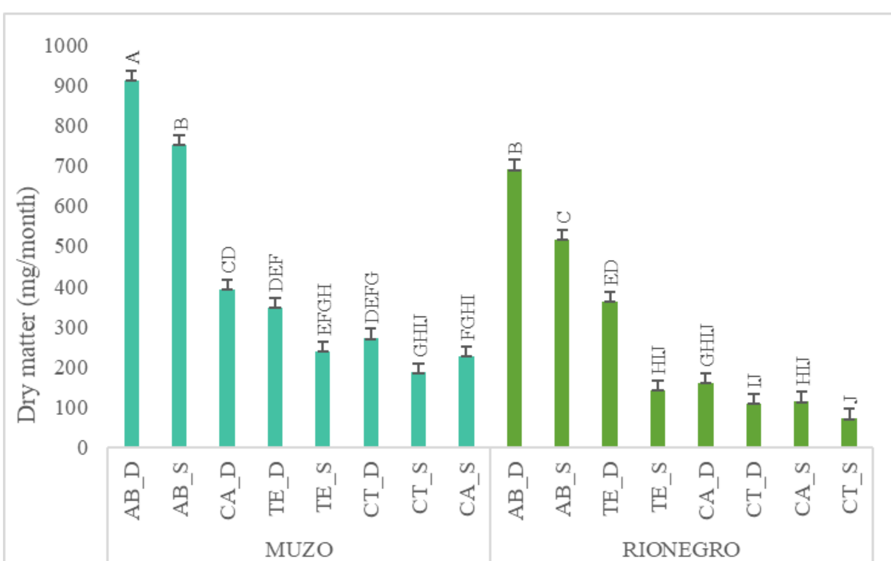

Figure 3. Average monthly litter production in an agroforestry system with cacao. Error bars correspond to standard error (P≤0.05).

Table 2. Estimated annual leaf litter production (kg ha^{-1} year^{-1}) under eight agroforestry treatments in two study sites (Muzo and Rionegro) in cacao-timber systems.

Treatment	Study site	
	Muzo	Rionegro
CM_D	3,279	2,484
CM_S	1,804	1,241
CCM_D	4,249	1,730
CCM_S	2,447	1,231
CT_D	2,919	1,172
CT_S	2,005	770
TE_D	1,253	1,306
TE_S	574	343

Note: Treatment abbreviations: TE = Teak monoculture, CM = Abarco (*Cariniana pyriformis*) monoculture, CT = TCS 19 cacao + Teak, CCM = TCS 19 cacao + Abarco; S = Single-row planting design, D = Double-row planting design.

For the climatic conditions in the Muzo location (relative humidity, rainfall, and temperature), the accumulation of litter in CM_S and CM_D is inversely correlated with rainfall (Rho = -0.8016), meaning that the greater the rainfall, the lower the accumulation of litter (Figure 4c).

In Rionegro, no significant correlation existed between climatic variables and the evaluated treatments' litter accumulation. The highest coefficient value was observed between the accumulated litter in CT_S, CT_D, CCM_S, and CCM_D and the relative humidity (Rho = -0.7129) (Figure 5b).

The highest contributions of N were presented in the litter from TE_S and TE_D, with average values of 1.5% at both sites. For the Ca element in both study sites, the highest values were observed in CT_S, with the highest value in Muzo (1.5%) and in Rionegro in CT_D (2.2%). The micronutrients with the highest concentration in the two study sites were Mn, followed by Fe, while the lowest values were present in elements B and Cu (Table 3). In Muzo, the highest contribution of Fe was presented in CCM_S (115.9 mg kg^{-1}), followed by TE_S (115.3 mg kg^{-1}); while, in the case of Mn, the highest values were found in CT_D, followed by CT_S (559.4 and 507 mg kg^{-1} respectively). The behaviour of these microelements in Rionegro differed, with the highest values of Fe being found in TE_S (94.68 mg kg^{-1}), followed by CM_S and TE_D (76.78 and 73.97 mg kg^{-1}, respectively), while, in the case of Mn, the highest values were found in CCM_D, followed by CT_S (878.8 and 669.6 mg kg^{-1}, respectively).

Considering the litter production potential in each study site, the nutritional content was estimated in kilograms per hectare (equation 2), and variations were presented by location and treatment (Table 4). The highest average nutrient contributions in both places are N and Ca.

$$\mathrm{CN}\ {}^{kg}/_{ha} = \frac{CNM \times NumA \times 12}{1000} \quad \text{(Equation 2)}$$

Where:
CN: Nutritional content
CNM: Nutritional content per monthly treatment
NumA: Number of trees per hectare

In Muzo, CCM_D treatment showed the highest values of N (56 kg ha^{-1}), P (2.5 kg ha^{-1}), Ca (51 kg ha^{-1}), Mg (24 kg ha^{-1}), and S (10 kg ha^{-1}), all exceeding the site average for these nutrients. In the case of Rionegro, CCM_D provided the highest contents of K (7.1 kg ha^{-1}), Ca (34 kg ha^{-1}), and Mg (14 kg ha^{-1}) compared to the other treatments evaluated.

Among micronutrients, Mn showed the highest content across both sites and treatments, ranging from 0.1 to 1.8 kg ha^{-1}, followed by Fe (0.1 to 0.8 kg ha^{-1}). In Muzo, the highest Mn values were observed in CCM_D (1.8 kg ha^{-1}) and CT_D (1.6 kg ha^{-1}), while Fe peaked in CM_D (0.8 kg ha^{-1}) and CM_S (0.6 kg ha^{-1}), and Zn reached its maximum in CCM_D and CCM_S (1.2 and 0.6 kg ha^{-1}, respectively). In Rionegro, CCM_D and CCM_S also presented the highest Mn contents (1.5 and 1.3 kg ha^{-1}), CM_D and CM_S showed the highest Fe values (0.5 and 0.4 kg ha^{-1}), while Zn content remained notably low with a maximum of only 0.1 kg ha^{-1}. Overall, treatments containing abarco showed consistently higher micronutrient contributions at both sites.

Leaf litter accumulation and nutritional content varied depending on the location where the trial was established and the interaction between these factors. A paired t-test was performed for each element to detect differences in nutritional content between sites. The analyses revealed statistically significant differences between Muzo and Rionegro for all elements except nitrogen (N) (Table 4).

Principal components analysis

With the estimated data of macronutrients in leaf litter, except for Na, a principal component analysis was performed. Considering the criterion of> 1, the first two components were retained, which explain 88.2% of the total variation in the data (Figure 6). For the first component (65.84 %), the elements with the highest weight were Ca, S, Mg, and N, and for the second (22.37 %), the element was Fe. The PCA biplot illustrates the relationship between treatments and nutrient variables, with CM_D and CM_S positioning closely with N, P, S, Ca, and Mg, whereas TE_S exhibits an opposite association. High K were associated with CT_D and CM_D, and Fe showed the strongest association with CM_D and CM_S (Figure 6).

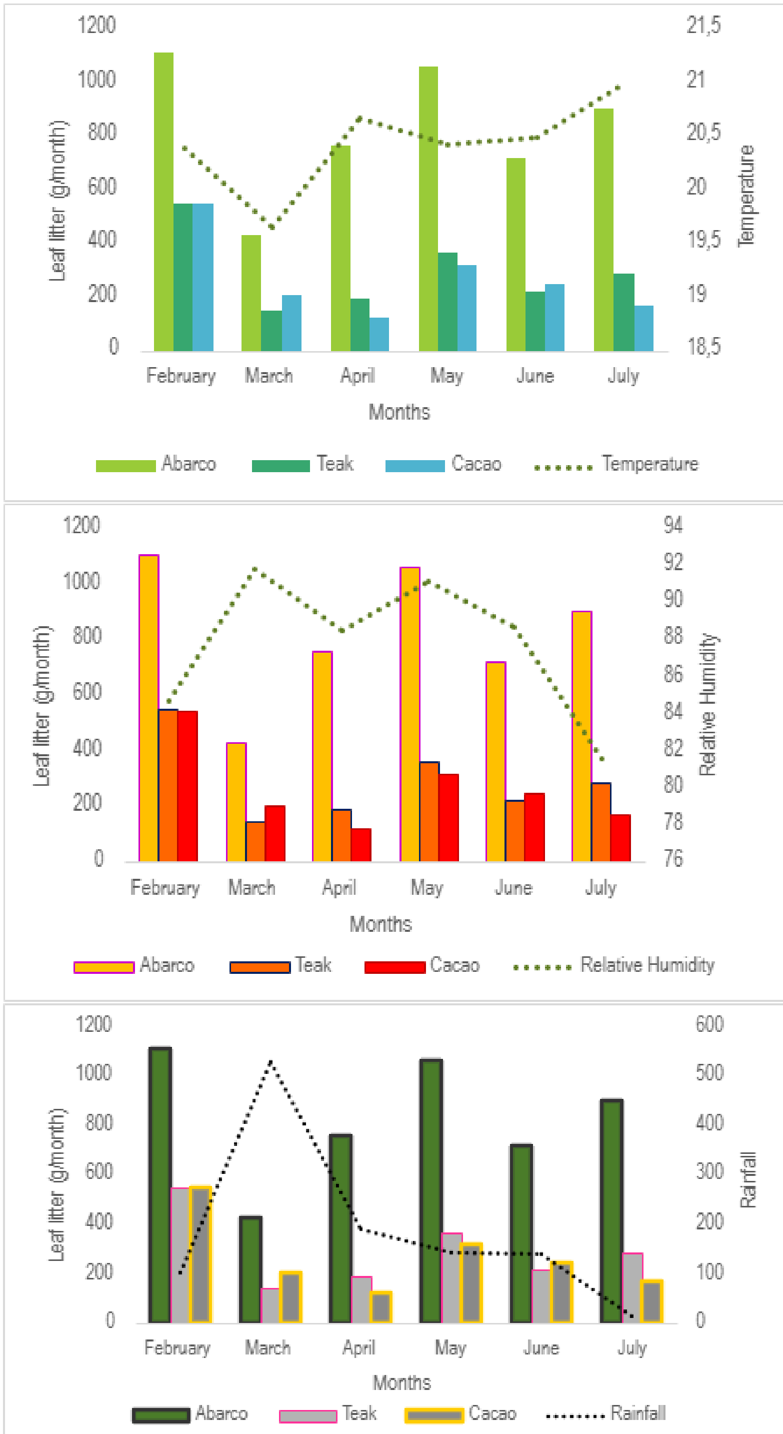

Figure 4. Litter contribution by species in Muzo related to a. Temperature, b. Relative humidity, and c. rainfall.

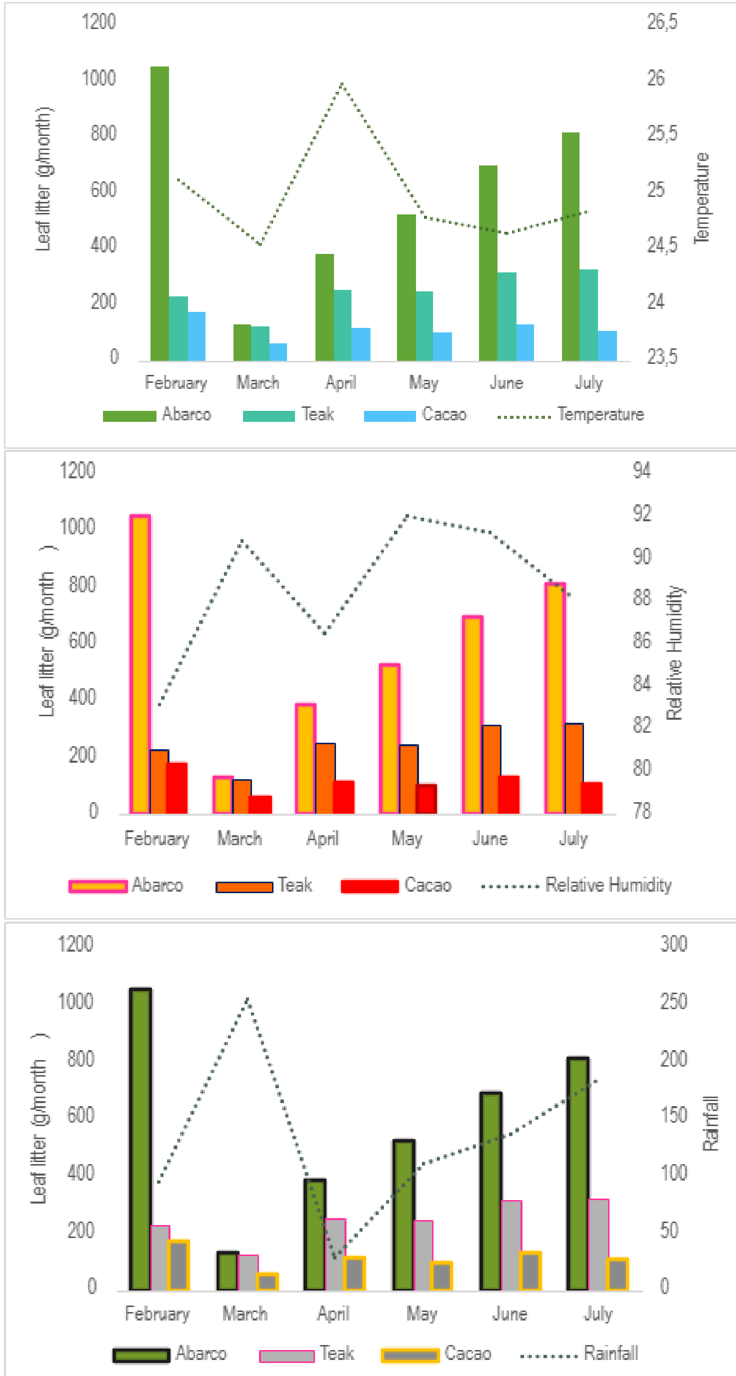

Figure 5. Litter contribution by the three species in Rionegro during the evaluation period vs.: a. Temperature, b. Relative humidity, c. Rainfall.

DISCUSSION

Rainfall affects litterfall production in production systems. The results of this study are consistent with those reported by Rodríguez et al. (2023), who found that rainfall affects leaf litter production in CAF. However, in some cases, this relationship is not evident since it depends on the contributing treatments. In addition, according to Rojas-Molina et al. (2021), it has been demonstrated that biomass production increases during dry seasons, possibly due to the plant's response to water stress. Furthermore, Asigbaase *et al.* (2021) found that annual litter accumulation was affected by seasonality, with a significant peak in the dry season and minor peaks during the rainy season. For the other variables and treatments, high correlation values were not observed.

Table 3. Nutrient concentration in leaf litter from eight agroforestry treatments at Muzo and Rionegro study sites, showing macronutrients (%) and micronutrients (mg kg⁻¹).

Locality	Treatment	Macronutrients (%)							Micronutrients (mg kg⁻¹)				
		N	P	K	Ca	Mg	Na	S	Fe	Cu	Mn	Zn	B
Muzo	CM_D	1.2	0.0	0.3	0.7	0.1	0.00	0.1	86.11	7.46	27.76	13.26	6.23
	CM_S	1.2	0.1	0.2	0.9	0.2	0.00	0.1	75.25	6.14	31.31	14.46	6.04
	CCM_D	1.3	0.1	0.6	1.2	0.6	0.00	0.2	86.78	5.72	422	280.4	18.2
	CCM_S	1.1	0.1	0.5	1.3	0.5	0.00	0.2	115.9	5.87	433.5	238.4	17.0
	CT_D	1.3	0.1	1.1	1.3	0.2	0.00	0.2	85.75	7.61	559.4	76.77	19.7
	CT_S	1.3	0.1	0.9	1.5	0.3	0.00	0.2	99.7	6.71	507.0	53.25	18.3
	TE_D	1.5	0.1	0.5	1.1	0.1	0.00	0.2	111.8	9.82	33.84	19.64	3.99
	TE_S	1.5	0.1	0.4	0.8	0.2	0.04	0.1	115.3	10.5	41.64	27.71	4.36
Rionegro	CM_D	1.2	0.0	0.2	1.0	0.4	0.00	0.1	66.25	3.92	49.08	12.83	25.6
	CM_S	1.3	0.1	0.2	0.8	0.4	0.00	0.1	76.78	6.23	123.7	21.78	15.2
	CCM_D	1.4	0.1	0.4	2.0	0.8	0.01	0.1	62.01	6.01	878.8	44.46	41.1
	CCM_S	1.3	0.1	0.5	1.3	0.9	0.00	0.2	50.53	9.78	1037.0	77.37	28.6
	CT_D	1.2	0.1	0.5	2.2	0.8	0.00	0.2	54.13	7.82	716.8	36.72	24.1
	CT_S	1.3	0.1	0.8	1.6	0.7	0.02	0.2	69.83	9.21	669.6	41.08	25.6
	TE_D	1.4	0.1	0.4	1.5	0.4	0.00	0.1	73.97	15.3	70.49	33.7	17.6
	TE_S	1.5	0.1	0.5	1.2	0.3	0.00	0.1	94.68	13.4	73.13	26.55	18.5

Note: Treatment abbreviations: TE = Teak monoculture, CM = Abarco (*Cariniana pyriformis*) monoculture, CT = TCS 19 cacao + Teak, CCM = TCS 19 cacao + Abarco; S = Single-row planting design, D = Double-row planting design.

Table 4. Nutritional contribution of leaf litter in macronutrients (%) and micronutrients (kg ha⁻¹) under eight agroforestry treatments at two study sites, with site means and statistical comparisons:

Sites	Treatment	Macronutrients							Micronutrients				
		N	P	K	Ca	Mg	Na	S	Fe	Cu	Mn	Zn	B
Muzo	CM_D	39	1.3	11	23	3.6	0.1	4.6	0.8	0.1	0.3	0.1	0.1
	CM_S	34	1.6	5.4	25	5.1	0.1	3.2	0.6	0.0	0.3	0.1	0.0
	CCM_D	56	2.5	23	51	24	0.1	10	0.4	0.0	1.8	1.2	0.1
	CCM_S	27	1.2	12	31	12	0.1	4.6	0.3	0.0	1.1	0.6	0.0
	CT_D	38	1.5	32	37	5.3	0.1	5.5	0.3	0.0	1.6	0.2	0.1
	CT_S	25	1.0	18	30	5.8	0.1	3.6	0.2	0.0	1.0	0.1	0.0
	TE_D	19	1.4	5.9	14	1	0.0	1.9	0.4	0.0	0.1	0.1	0.0
	TE_S	13	0.9	3.4	6.9	2.1	0.3	1.1	0.3	0.0	0.1	0.1	0.0
	Mean	31.4	1.4	14.0	27.3	7.4	0.1	4.3	0.4	0.01	0.7	0.3	0.04
	S.E.	5.1	0.2	3.5	4.8	2.5	0.03	0.9	0.08	0.01	0.2	0.1	0.02
Rionegro	CM_D	30	1.0	3.7	25	9.4	0.1	3.5	0.5	0.0	0.4	0.1	0.2
	CM_S	24	0.9	3.9	15	7.3	0.1	2.4	0.4	0.0	0.7	0.1	0.1
	CCM_D	24	1.4	7.1	34	14	0.1	2.1	0.1	0.0	1.5	0.1	0.1
	CCM_S	16	0.9	5.5	16	11	0.0	2.0	0.1	0.0	1.3	0.1	0.0
	CT_D	15	0.9	5.7	26	9.8	0.0	1.8	0.1	0.0	0.8	0.0	0.0
	CT_S	9.9	0.7	6.3	12	5.5	0.2	1.2	0.1	0.0	0.5	0.0	0.0
	TE_D	18	1.8	5.4	19	4.8	0.0	1.4	0.3	0.1	0.3	0.1	0.1
	TE_S	7.7	0.7	2.3	6.3	1.7	0.0	0.6	0.1	0.0	0.1	0.0	0.0
	Mean	18.1	1.0	5.0	19.2	7.8	0.06	1.8	0.2	0.01	0.7	0.06	0.05
	S.E.	2.8	0.1	0.6	3.4	1.2	0.02	0.3	0.05	0.01	0.2	0.02	0.02

Note: Treatment abbreviations: TE = Teak monoculture, CM = Abarco (*Cariniana pyriformis*) monoculture, CT = TCS 19 cacao + Teak, CCM = TCS 19 cacao + Abarco; S = Single-row planting design, D = Double-row planting design.

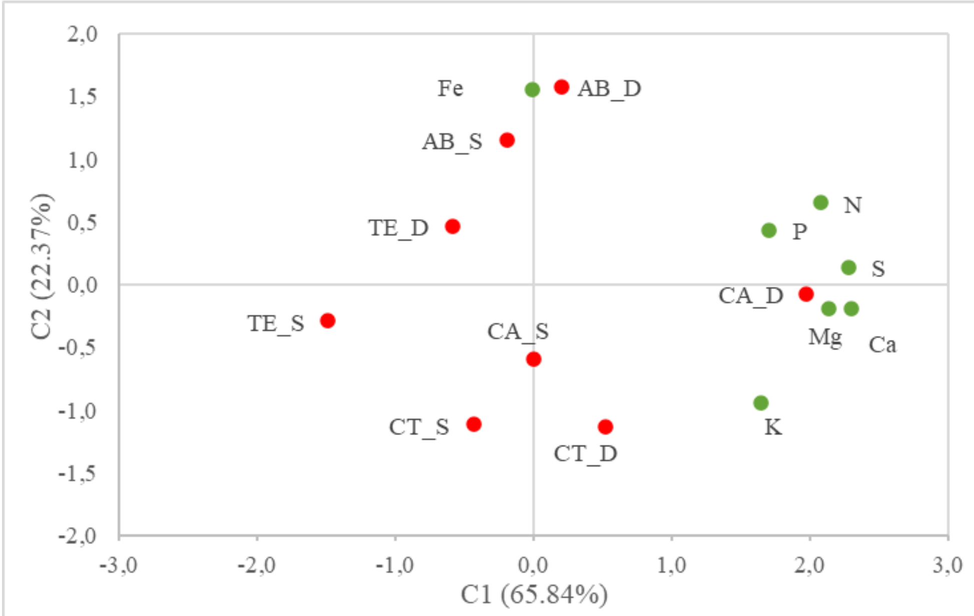

Figure 6. Principal components for accumulating nutrients in the plant tissue of species associated with the agroforestry system with cacao. Green - treatments and Red – nutrients.
Note: Treatment abbreviations: TE = Teak monoculture, CM = Abarco (*Cariniana pyriformis*) monoculture, CT = TCS 19 cacao + Teak, CCM = TCS 19 cacao + Abarco; S = Single-row planting design, D = Double-row planting design.

Similar results were found by Arcos and Jaimez (2020), who reported a decrease in litter from trees in seasonal climates, mainly during humid seasons. However, they stated that in non-seasonal climates such as tropical rainforests, the most remarkable litterfall occurs during periods of greater rainfall due to the mechanical action of the on-plant foliage.

The highest litter contribution by the evaluated species was recorded during the dry period (Figures 4c and 5c), possibly because plants shed leaves to reduce water consumption (Ngaiwi *et al.*, 2018). The low water availability in soil during the dry season causes a physiological response in cacao treatments (CT_S, CT_D, CCM_S, CCM_D) and their shade trees (TE_S, TE_D, CM_S, CM_D) as a drought response, causing the trees to shed leaves to reduce evapotranspiration (Sari *et al.*, 2022).

Other factors, such as damage to the leaf blade or senescence due to the life cycle, as well as meteorological conditions (rainfall, temperature, and relative humidity), play an essential role in the physiological changes of plants, especially when they face periods of stress (Fuentes *et al.*, 2018; Ngaiwi *et al.*, 2018). Similar patterns of litter accumulation have been observed in cacao ecosystems, with the volume of litter varying according to the treatment and planting system (Rodríguez *et al.*, 2023). The highest litter contribution by the evaluated treatments was recorded during the dry period (Figures 4c and 5c), possibly because plants remove leaves to reduce water consumption (Ngaiwi *et al.*, 2018).

TE_S, TE_D, CM_S, and CM_D serve as a source of nutrients with a higher quality than CT_S, CT_D, CCM_S, and CCM_D litter, although they are used as a sink (Asigbaase *et al.*, 2021). For this reason, understanding the composition of leaf litter and its decomposition rate is crucial for influencing the physical, chemical, and biological properties of the soil. This knowledge is essential to maximise the positive impact of plant residues on soil quality enhancement. Additionally, it is crucial to synchronise the release of nutrients from residue decomposition with plant nutrient uptake patterns (Fontes *et al.*, 2014; Akinsola *et al.*, 2024). Generally, a rise in soil fertility correlates positively with the leaf litter quality, nutrient concentrations in live leaf tissue, decomposition rates, and nitrogen mineralisation (Bai *et al.*, 2022; Akinsola *et al.*, 2024).

Regarding the nutrient content in the litter, the highest concentrations of macronutrients were found for N, followed by Ca in both study sites (Table 3). This occurs because the highest N contents are found in litter compared to other plant organs, and Ca content is also high because this is an immobile element in the vascular system, and plants cannot reabsorb it (Ngaiwi *et al.*, 2018). When analysing the nutritional contribution of litter, it can be organised as follows: N > Ca > K > Mg > S > P > Na. Similar behaviour occurs in Muzo. However, in Rionegro, the contribution varies slightly, with Ca being the highest, followed by N, results consistent with those reported for CT_S, CT_D, CCM_S, and CCM_D (Mohammed *et al.*, 2020). These site-specific differences in nutritional patterns can be attributed to variations in climatic and edaphic conditions between locations. Environmental factors such as temperature, rainfall distribution, and soil properties directly influence nutrient availability and plant uptake processes, ultimately affecting the elemental composition of leaf litter.

In this study, the nutrient concentration values in TE_S and TE_D are similar to those reported in other studies (Arcos and Jaimez, 2020; Murillo *et al.*, 2014), which evaluated the nutritional contribution for four years for this species. The same occurs with CT_S, CT_D, CCM_S, and CCM_D, where the nutritional composition values correspond to those reported by Rosas-Patiño et al. (2021), who also found a clone-treatment interaction. These nutrient concentration values in leaf litter indicate the potential of these treatments in the nutrient cycle (Mohammed *et al.*, 2020). The combination of commercial cacao with high leaf litter production forest species could increase nutrient availability and benefit crops with high nutrient demand (Kaba, 2017). Concerning the Mn contents, the highest values were observed in CT_S and CT_D (1,037 mg kg^{-1} for single-rows and 878 mg kg^{-1} for double-rows, respectively). Mohammed *et al.* (2020) found that cacao litter presents the lowest values of the concentration of nutrients such as Mn and Fe. However, when the TE_S, TE_D, CM_S, and CM_D are evaluated, these values are slightly higher, which indicates that these shade tree treatments contribute to soil fertility. Rangel and Silva (2020) found that Cacao is a species that has a higher content of elements (N, K, S, and Mg) in its leaf litter compared to other species established in CAF systems. The inverse relationship of the nutritional contents of the leaf litter from TE_S and TE_D in comparison may be due to the conditions, since it has been shown that for this species, factors such as age and soil conditions affect the contents of K, Mg, N, and Fe (Figure 6) (Fernández *et al.*, 2013).

In a study by Rojas *et al.* (2021), different chemical and organic fertilization treatments were evaluated on the nutrient contribution of leaf litter in *T. cacao* plant material. The values reported by these authors differ from those found in this study, likely because the conditions in the study areas were different and the fertilization plans had an impact.

CONCLUSIONS

The tropical hardwood agroforestry system, featuring cacao, whether planted in single or double rows, provides significant nutritional value due to the litter produced during its physiological and productive development. These nutrients are released through the decomposition and organic matter production and returned to the soil, improving its composition. Of the treatments evaluated, CM_S and CM_D made significant contributions regardless of the planting system. When combined with cacao cultivation (CCM_S and CCM_D), they offer the opportunity to improve not only productivity but also nutrient cycling.

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Data availability. The data collected in the present study are available in electronic format with corresponding author.

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