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Abstract

Cocoa-based agroforestry systems (AFS) are a key strategy for strengthening agronomic and economic sustainability in tropical regions; therefore, comprehensive knowledge of cocoa-based AFS is essential. This study characterized 12 plots in the province of Utcubamba, Amazonas (Peru), by evaluating indicators of tree diversity, canopy structure, soil fertility, the presence of major pests and diseases, and economic performance. Tree diversity and structure revealed functionally differentiated communities, reflected in Shannon index values of H′ = 2.24, canopy cover exceeding 60%, and importance value indices (IVI) highlighting dominant species such as *Calycophyllum spruceanum* (16.79%) and *Laurus nobilis* (15.64%), which contribute to microclimatic regulation and system resilience. Soil analyses showed a strong correlation between organic carbon, organic matter, and nitrogen ($r > 0.95$; $r = 1.00$ between C and O.M.), emphasizing the role of organic matter management in improving soil quality and crop productivity, with organic carbon ranging from 1.91% to 3.89%, organic matter from 3.30% to 6.71%, and total nitrogen from 1.65% to 3.35%. Pest incidence exhibited low or insignificant correlations with soil parameters ($r \leq 0.32$) and generally moderate levels, suggesting a stronger influence of management practices, shade structure, and local environmental conditions. Economically, AFS showed an average profit of USD 2,616.20, influenced by plantation age (≈7 years), technification level, and labor availability. Overall, cocoa-based AFS function as multifunctional systems capable of simultaneously enhancing productivity, ecological stability, and economic sustainability in the region.

Keywords: Cocoa agroforestry systems**;** Dry Forests; Tree diversity; Soil fertility; Sustainable agriculture.

I. INTRODUCTION

Agroforestry, defined as the intentional integration of trees, crops, and/or livestock within a management unit (AFS), is a key strategy for promoting more sustainable and resilient agricultural systems (Castillo et al. 2024). AFS, classified as sequential and simultaneous according to Atangana et al. (2024), are recognized for their ability to increase production, diversify income, improve ecosystem service provision (including climate regulation), and promote multifunctional agriculture multifunctional agriculture that allows for diversification of production and increased yields (MIDAGRI 2021). In the context of climate change, SAFs are considered essential adaptation practices due to their ability to moderate the microclimate by reducing air and leaf temperatures by between 2 and 5 °C under shade (Brown et al. 2018; Merle et al. 2022; Montagnini et al. 2015). Agroforestry systems also contribute to the fulfillment of the Sustainable Development Goals (SDGs) related to strengthening agricultural resilience, mitigating climate impacts, and conserving biodiversity (United Nations, 2015).

Cocoa (*Theobroma cacao* L.) agroforestry represents one of the most studied AFS, given that farmers intentionally integrate shade trees with cocoa plantations and other food crops on the same plot (Asigbaase et al. 2019). The presence of shade reduces physiological stress in cocoa and contributes to natural pest control, the incidence of which tends to increase in monocultures in full sun due to more extreme conditions and structural homogeneity (Suárez et al. 2025; Armengot et al. 2020). However, management dilemmas persist regarding the optimal level of shade. More conservative farmers tend to maintain greater tree cover to reduce risks and protect crops from pests, prioritizing the long-term stability of the system. In contrast, producers focused on maximizing yield tend to reduce shade to increase immediate productivity, even if this means greater future vulnerability of the system (Tscharntke et al. 2011). Therefore, despite various studies on cocoa management in tropical landscapes (Tscharntke et al. 2011; Somarriba et al. 2021), there are still significant gaps in our understanding of how agronomic and economic decisions interact within SAFs and condition the sustainability of the system under different socio-environmental contexts.

Cocoa (*Theobroma cacao* L.) is a crop of high strategic value in international markets due to its importance for the chocolate industry, as well as its nutritional and organoleptic attributes (López et al., 2020). Peru is part of the center of origin of cocoa and is recognized worldwide for its natural characteristics, fine flavor and aroma Buyer et al. (2017). Currently, the country is considered the third largest exporter of organic cocoa worldwide, with more than 165,800 tons produced between 2023 and 2024 (Gutiérrez 2024). However, like other producing countries, it faces structural constraints such as low farm prices, high input costs, limited access to credit, smallholdings, declining soil fertility, and inadequate pest and disease management (Keller et al. 2025; Antolinez et al. 2020). These limitations compromise productivity and economic stability, which are reflected in the quality of life of producers. Quality of life is a critical and often underestimated component of agricultural sustainability (Ye & Zhang 2025).

At the regional level, the department of Amazonas is a key territory for cocoa production in Peru, as it has the bioclimatic and sociocultural conditions that favor the expansion of agroforestry systems. Among the main agricultural drivers, cocoa is a strategic crop involving more than 7,800 producers on nearly 10,000 ha, whose territorial identity is reflected in the Amazonas Peru Cocoa Designation of Origin (APPC 2022; GOREA 2025). However, production systems vary considerably within the region: while shaded SAF predominate in the Awajún territories of Condorcanqui, in Bagua cocoa is usually grown on open plots of less than 5 ha and is often associated with Musa spp. (Fernández Jeri et al. 2022; Goñas et al. 2022). Recent initiatives led by cooperatives and local programs have promoted the integration of native species and sustainable practices to improve the microclimate and productivity in districts such as Copallín, Imaza, La Peca, Aramango, and Nieva (Plan Binacional de Desarrollo de la Región Fronteriza Perú - Ecuador 2022; Rikolto 2023). However, a critical gap remains in the comprehensive characterization of cocoa SAFs in Amazonas, as most studies focus on biophysical or economic aspects separately, without assessing how agronomic practices, system structure, and economic conditions interact. This limits our understanding of productive sustainability and farmer well-being.

In this context and given the scarcity of studies jointly integrating the agronomic and economic performance of cocoa-based AFS in the department of Amazonas, Peru, a comprehensive characterization is needed to better understand how management practices influence productivity and the economic sustainability of producers. Therefore, this study aimed to (i) characterize key agronomic variables of cocoa-based agroforestry systems, (ii) analyze the main economic variables, and (iii) evaluate the relationships between these components to provide an integrated understanding of the functioning and sustainability of these systems in the region.

II. MATERIALS AND METHODS

2.1. Study area

The province of Utcubamba (Figure 1a), located in the central zone of the department of Amazonas (Figure 1b), in northwestern Peru (Figure 1c), has a warm climate characterized by maximum temperatures that can reach 40 °C in summer and minimum temperatures around 18 °C in winter (SENAMHI 2018). Precipitation is characterized by falling between 600 and 800 mm, concentrated mainly during the first half of the year. These conditions coincide with the optimal ranges for cocoa cultivation described by Arevalo et al. (2017) which favors the establishment of productive SAFs. In this context, the 12 SAF plots evaluated in this study, all located below 1,000 meters above sea level and managed under association schemes with shade species, are located in the district of Cajaruro, province of Utcubamba (Fig. 1a). In this province, agriculture is the main local economic activity, complemented by temporary crops such as rice, coffee, and bananas (IGP 2021). which reinforces the importance of cocoa as the dominant productive sector in the area.

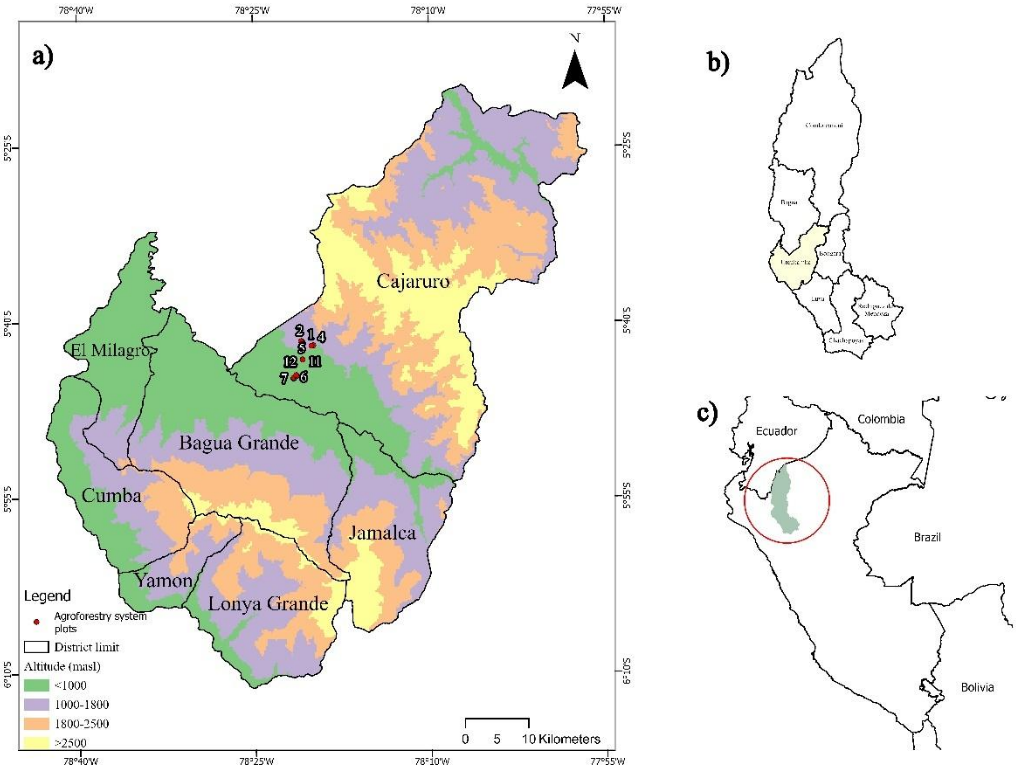

Figure 1. Study area showing the 12 cocoa-based agroforestry system (AFS) plots (a), located in the province of Utcubamba, in the central part of the Amazonas department (b), northern Peru (c).

2.2. Methodological flowchart

The study methodology (Figure 2) was structured into five stages. First (i), satellite information was used to identify and preselect plots representative of cocoa cultivation. Second (ii), soil sampling was conducted in the selected plots, and samples were analyzed in the laboratory to determine chemical parameters, including organic matter, organic carbon, pH, total nitrogen, available phosphorus, and available potassium, as well as the physical parameter of electrical conductivity. Third (iii), soil and agronomic conditions were characterized by considering the presence of pests and diseases and cocoa yield. Fourth (iv), economic characteristics were assessed through the calculation of production costs, revenues, and the benefit–cost ratio. Finally (v), statistical analyses were applied to comprehensively evaluate the relationships among soil, agronomic, and economic variables in order to understand their combined influence on cocoa productive performance.

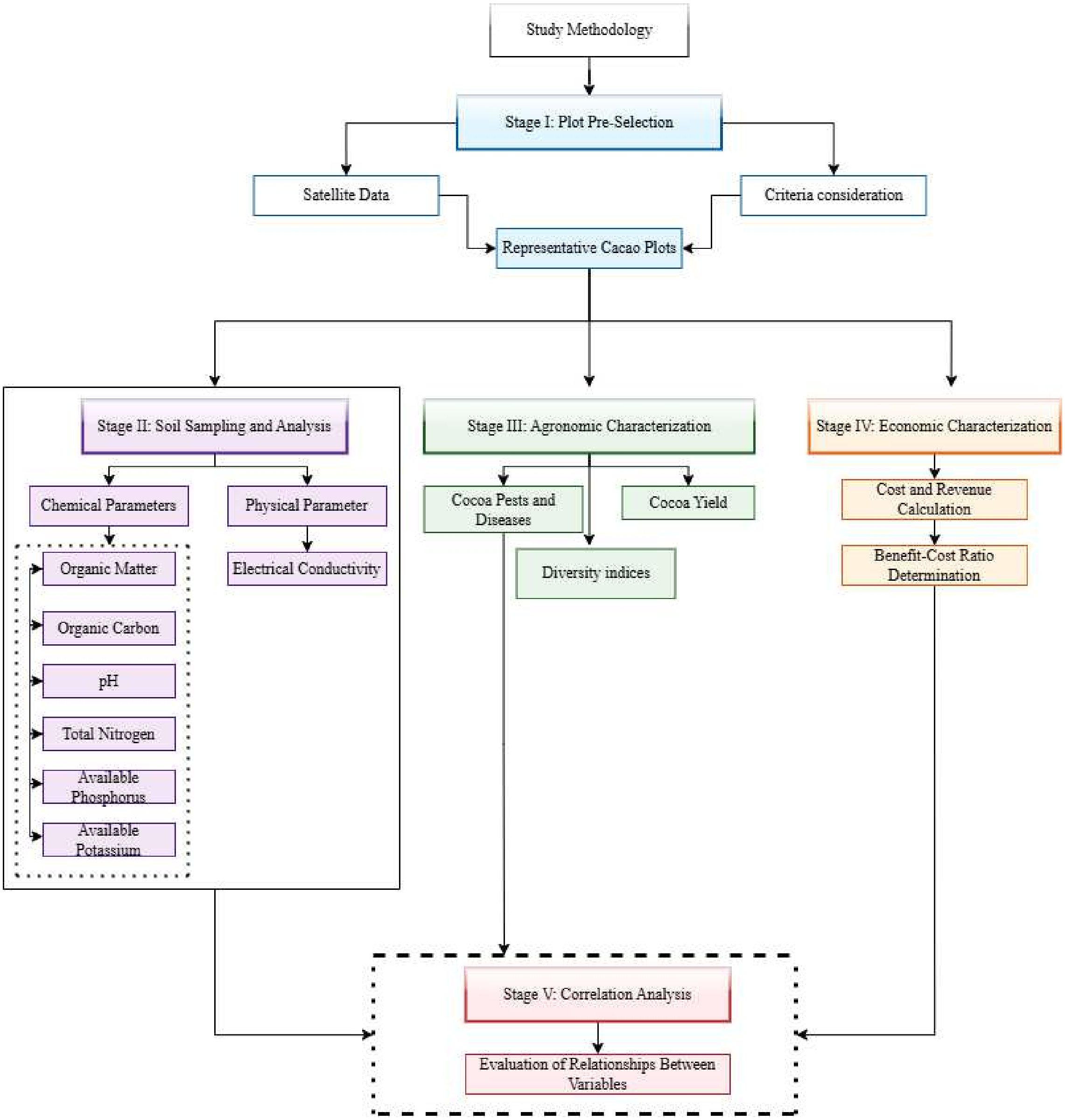

Figure 2. Research methodology process.

2.3. Parcel delimitation

The research was conducted using non-probabilistic purposive sampling, coordinated with producers from the Central Agricultural Producers' Cooperative of Amazonas (CEPROAA). In the first phase, the population centers with the highest cocoa production were identified using official information from the association, restricting participation to farmers located within these areas. In the following step, the willingness of producers to participate in the study was verified and their informed consent was obtained (Hernández & Mendoza 2018).

As a result, 12 plots were selected in the province of Utcubamba, primarily in the district of Cajaruro. The selection was based on the criteria described in Table 1, which included: (a) a minimum area of 1 ha, (b) the presence of at least five tree species with a diameter at breast height (DBH) greater than 10 cm, (c) accessibility of the plot for technical evaluation, and (d) compliance with the ethical requirement of producer consent (Somarriba 2009).

Table 1. Criteria for including and excluding plots for selection.

Indicator	Inclusion	Discard
Area	≥1 ha.	< 1 ha.
Cocoa variety	CCN - 51	Other varieties
DBH	≥10	<10
Presence of M. roreri and M. dissimulatum Dist.	Yes	No
Production status	In production	No production
Access	Access by road	No road access
Producer consent	Participates in the study	Not participating in the study

2.4. Spatial characterization of plots with AFS

In each of the selected plots, boundary survey was conducted accompanied by the producer in order to identify the tree species present. Identification was carried out through direct observation, verifying the common names of tree species according to the farmer's local knowledge. During the inventory, the diameter at breast height (DBH) was recorded at a standard measurement of 1.30 m above the ground, considering only individuals with a DBH greater than 10 cm, since trees with a smaller DBH may have high mortality and irregular growth (Phillips et al. 2021). Canopy cover was estimated using a concave spherical densitometer (James C. Doster model), aking four readings per plot in the north, south, east, and west directions, whose values were then averaged. Likewise, canopy opening was calculated using the formula proposed by Lemmon (1956), multiplying the number of opening points recorded by a conversion factor of 1.04 to estimate canopy openness.

$$Shade\ (\%) = \left(\frac{\sum N}{96}\right) x\ 100\ x\ 1.04 \qquad (1)$$

$\sum N$: Total points with cup

96: Total points from spherical densitometer

100: Factor for expressing as a percentage

1.04: Conversion factor proposed by Lemmon (1956)

2.5. Importance value index

The Importance Value Index (IVI) was used to assess the ecological relevance of species within the AFS in the study area, based on the classic methodology originally proposed by Curtis & Mcintosh (1951). The equations used were:

$$Relative\ density\ (\%) = \frac{Density\ of\ a\ species}{Total\ density\ of\ all\ species} x100 \qquad (2)$$

$$Canopy\ coverage\ (\%) = \frac{Canopy\ coverage\ of\ a\ species}{Total\ coverage\ of\ all\ species} x100 \quad (3)$$

$$Relative\ frequency\ (\%) = \frac{Frequency\ value\ of\ the\ species}{Sum\ of\ frequencies\ of\ the\ species\ studied} x100 \quad (4)$$

$$\mathrm{IVI} = \mathrm{RD} + \mathrm{CC} + \mathrm{RF} \quad (5)$$

2.6. Assessment of the incidence and severity of pests and diseases

The incidence of cocoa moniliasis caused by *Moniliophthora roreri* was estimated for each plot. Each sampling unit was divided into three strata, from which five to six fruits were selected per stratum, for a total of 20 fruits evaluated per plot, with one fruit assessed per plant, following the scale and formula proposed by (CATIE 2007):

$$\mathrm{Incidence}\ (\%) = \frac{Number\ of\ infected\ ears}{Total\ number\ of\ ears\ evaluated} x100 \quad (6)$$

Similarly, infestation by *Monalonion dissimulatum* Dist. was assessed using fruits collected from the same cocoa plants evaluated for *M. roreri*. Five cocoa plants were selected per plot, and infestation severity was classified using the pictorial scale proposed by Vargas et al. (2005), as shown in Table 2. All analyses were conducted at the Cacao Research Center of the National University Toribio Rodríguez de Mendoza (CEINCACAO).

Table 2. Severity scale for M. dissimulatum Dist.

Scale	Magnitude (%)	Characterization
0	0	Healthy fruit, without lesions
1	5	Small spots
2	6 – 20	Scattered spots
3	21 – 40	Partial necrosis
4	41 – 60	Severe damage
5	61 – 100	Very severe damage

The pictorial scale is based on the classification of cocoa pods according to their morphological dimensions, using parameters such as length, diameter, and apparent volume (Huaycho et al. 2017). This scale enables the differentiation of morphological categories that are useful for agronomic characterization, selection of genetic material, and quality assessment within production systems (Figure 3).

Figure 3. Pictorial scale developed in this study showing damage severity categories caused by *Monalonion dissimulatum* Dist. on cocoa pods (*Theobroma cacao* L.).

2.7. Soil sampling and analysis

Soil sampling at a depth of 0 –30 cm was conducted to analyze the physical, chemical, and biological properties of the soil, allowing its fertility and quality to be characterized (Santos et al. 2017). In this part, a stratified random sampling was designed, which depended on the heterogeneity of the terrain, considering homogeneous units defined by crop type or management practices (Pacciorett et al. 2020).

In each unit, between 10 and 15 subsamples were collected using a regular grid pattern, then homogenized to form a representative composite sample following Antonio & Marrero (2025). The subsamples were extracted with a spade, removing vegetation debris and stones, and the geographic location was recorded using a GNSS receiver, together with the sampling date, soil type, and site conditions (Calle et al. 2023).

The samples were placed in clean bags, labeled with basic data (code, coordinates, depth, date, and name of the sampler), and transported to the laboratory at room temperature as indicated by Francisco-Santiago et al. (2023). In the laboratory, the samples were air-dried, sieved to 2 mm, and stored for the corresponding analyses. In addition, quality controls (field duplicates, blanks, and reference samples) were implemented to ensure the representativeness of the results. This procedure was based on standardized methodologies proposed by the FAO (2006), Carter y Gregorich (2007) y Schoeneberger et al. (2002), which highlight the importance of adequate sampling to ensure the reliability of the analysis.

2.8. Economic evaluation of AFS

Of the twenty cocoa pods selected as described in Section 2.5, a selective harvest of ripe pods was conducted following standard post-harvest methodologies. The pods were opened and the cocoa beans were extracted, weighed, washed, and subjected to a fermentation process lasting 48–72 h, in accordance with recommended practices for fine-flavor cocoa and commercial use (Lagos et al. 2024). After this process, the beans were dried and sorted, and dry bean yield was calculated using the formula proposed by Córdova et al. (2016).

$$Yield\ (kg/ha) = \frac{Total\ mass\ of\ ears\ harvested\ (kg)}{Surveyed\ area\ (ha)} \quad (7)$$

2.8.1 Production costs

Production cost data were obtained through field surveys conducted with producers and were classified into direct and indirect costs. Direct costs included inputs, equipment and tools, labor, transportation, and post-harvest processing expenses, whereas indirect costs comprised administrative costs, infrastructure, and basic services.

2.8.2 Cost-benefit

The cost–benefit ratio (B/C) was subsequently calculated, where values less than or equal to 1 indicate economic losses, while values greater than 1 indicate profitability over time. The B/C ratio was calculated using Equation 8:

$$\frac{\sum b}{\sum c} = \frac{B}{C} \qquad (8)$$

Where B represents total profits and C represents total costs.

2.9 Calculation of diversity indices

Diversity indices were calculated using species abundance data recorded in each sampling unit, with the aim of quantifying species richness, evenness, and dominance within plant and agroforestry communities. First, species richness (S) and the total number of individuals (N) present in each evaluated plot were determined.

From this data, the Margalef index was calculated using formula 9:

$$D_{Mg} = \frac{(S-1)}{ln(N)} \qquad (9)$$

Where,

ln: natural logarithm

Higher values indicate a more diverse community in terms of number of species. Next, the Shannon-Wiener index (H') was calculated using formula 10:

$$H' = -\sum piln(pi) \qquad (10)$$

This index will reflect both the richness and equity of the community, being higher when species have similar abundances (Marrugan, 2004). The Simpson index reflects both the richness and evenness of the community, being higher when species have similar abundances. It is defined by formula 11:

$$1 - D = 1 - \sum Pi^2 \qquad (11)$$

2.10 Data analysis

Data analysis was performed in R v.4.5.1 (R Core Team 2025), after organizing the field data in Microsoft Excel. The packages ggplot2 (Wickham, 2016), vegan (Oksanen et al. 2019), BiodiversityR (Kindt and Coe 2005), and factoextra (Kassambara 2024) were used for data processing and analysis. The specific package versions were recorded to ensure reproducibility, allowing other researchers to run the code under the same computational environment and obtain identical results.

To evaluate relationships between agronomic and economic variables and soil physicochemical properties, a Pearson correlation matrix was constructed to assess the strength and direction of linear associations among variables. Diversity indices were calculated within the same analytical framework. Prior to the economic analysis, the benefit–cost (B/C) ratio for the 12 cocoa-based AFS plots was estimated in Microsoft Excel, following the criteria and assumptions described by (Ballesteros et al. 2021) .

III. RESULTS

3.1 Comprehensive characterization of agroforestry systems

The tree structure of the AFS exhibited a community organization with clearly differentiated ecological roles, as reflected by the IVI. *Calycophyllum spruceanum* (IVI 16.79%; Figure 3a) and *Laurus nobilis* (IVI 15.64%; Figure 3b) were the most representative species owing to their high density and frequency, indicating a wide distribution across the plots. In contrast, *Mauritia flexuosa* (IVI 9.15%) was characterized by a high contribution to basal area, reflecting the presence of a limited number of large individuals that play a key role in shaping the canopy structure.

Table 4 presents the IVI values for all recorded species. *Citrus reticulata* and *Artocarpus altilis*, despite exhibiting low density, made a substantial contribution to basal area, suggesting that their larger size is associated with productive value for farmers. An intermediate group comprising *Psidium guajava*, *Mangifera indica*, and *Corymbia torelliana* contributes functional and productive diversity as well as economic value, without achieving structural dominance within the system. Overall, most species exhibited IVI values below 2%, indicating low spatial representation and/or limited structural contribution.

Table 4. IVI of tree species in cocoa-based AFS, where Density (%) corresponds to relative density, Basal area (%) to relative basal area, and Frequency (%) to relative frequency.

Species	Density (%)	Basal area (%)	Frequency (%)	IVI (%)
Laurus nobilis L.	29.17	2.99	14.75	15.64
Inga edulis Mart	3.21	2.45	6.56	4.07
Persea americana Mill.	2.56	1.99	4.92	3.16
Cordia alliodora (Ruiz & Pav.) Oken	1.28	1.99	1.64	1.64
Calycophyllum spruceanum (Benth.) Hook.f. ex K.Schum.	34.62	1.01	14.75	16.79
Cupressus Lusitanica Mill.	0.64	1.46	1.64	1.25
Acrocarpus fraxinifolius Wight & Arn.	1.28	2.12	1.64	1.68
Annona muricata L.	0.96	2.99	1.64	1.86
Croton lechleri Müll. Arg.	0.64	3.75	1.64	2.01
Hura crepitans L.	0.32	3.53	1.64	1.83
Eriobotrya japonica (Thunb.) Lindl.	0.32	1.15	1.64	1.04
Calycophyllum multiflorum Griseb.	0.64	2.27	4.92	2.61
Aspidosperma excelsum Benth.	0.32	0.62	1.64	0.86
Citrus reticulata Blanco	0.96	10.57	1.64	4.39
Chrysophyllum cainito L.	0.32	1.54	1.64	1.17
Caryodendron orinocense H.Karst.	0.32	0.95	3.28	1.52
Quercus robur L.	0.96	3.26	1.64	1.95
Spondias dulcis Parkinson	1.28	0.65	1.64	1.19
Corymbia torelliana (F.Muell.) K.D.Hill & L.A.S. Johnson	1.28	8	3.28	4.19
Cedrela odorata L.	0.32	1.01	1.64	0.99
Colubrina glandulosa Perkins	2.88	0.48	1.64	1.67
Syzygium jambos (L.) Alston	1.6	1.88	4.92	2.8
Mangifera indica L.	4.81	2.26	1.64	2.9

Psidium guajava L.	1.6	3.49	4.92	3.34
Matisia cordata Bonpl.	1.6	0.64	1.64	1.29
Artocarpus altilis (Park.) Fosb.	0.32	10.94	1.64	4.3
Tamarindus indica L.	1.6	1.67	1.64	1.64
Cocos nucifera L.	2.56	1.77	4.92	3.08
Mauritia flexuosa L. f.	1.6	22.56	3.28	9.15

Figure 4. Tree species recorded in the cocoa-based AFS with cacao (*Theobroma cacao* L.): (a) *Laurus nobilis* L.; (b, d) *Cocos nucifera* L.; (c) *Calycophyllum spruceanum* (Benth.) Hook.f. ex K. Schum.

3.2. Physicochemical analysis of soil

The physicochemical properties presented in Table 5 indicate that soils across the evaluated plots exhibited an alkaline reaction, with pH values ranging from 7.84 to 8.42. Electrical conductivity values were moderate (13.89–21.07 mS m^{-1}), indicating the absence of severe salinity constraints and generally suitable conditions for cocoa development. Nitrogen content ranged from low to moderate, whereas available phosphorus showed high variability among plots (11.01–37.43 ppm), reflecting differences in soil fertility and management practices associated with each agroforestry system. Exchangeable potassium concentrations were consistently high, favoring cocoa growth and productivity. Organic carbon (1.91–3.89%) and organic matter (3.30–6.71%) contents were within low to moderate ranges, highlighting the need to strengthen management practices aimed at increasing soil organic matter.

Table 5. Physicochemical properties of soils in the evaluated cocoa-based AFS plots, including pH, electrical conductivity (EC), total nitrogen (N), available phosphorus (P), exchangeable potassium (K), organic carbon (C), and organic matter (OM).

Parcela	pH (pH)	EC (mS/m)	N (%)	P (ppm)	K (ppm)	Carbono (%)	M.O (%)
1	8.18	16.88	2.46	11.01	428.25	2.86	4.93
2	8.19	20.49	3.35	16.81	467.8	3.89	6.71
3	7.99	18.42	2.01	29.76	502.29	2.33	4.02
4	7.84	21.07	2.56	18.89	614.55	2.97	5.12
5	8.42	17.61	1.84	22.93	391.68	2.13	3.68
6	7.93	19.81	1.84	16.61	440.21	2.13	3.68
7	8.19	19.21	2.31	13.29	676.87	2.68	4.62
8	8.19	15.19	2.42	11.22	630.31	2.81	4.85
9	8.37	18.58	2.46	13.19	532.48	2.86	4.93
10	8.34	16.63	1.86	37.43	436.58	2.15	3.71
11	8.03	16.29	1.65	28.93	488.99	1.91	3.3
12	8.4	13.89	2.77	24.17	514.3	3.21	5.53

3.3 Diversity indices

The calculated diversity indices indicate a structurally heterogeneous and functionally diverse plant community (Table 6). The Margalef index (5.21) reflects relatively high species richness adjusted for sample size, suggesting that the cocoa-based agroforestry systems (AFS) host a wide range of tree species. The Shannon–Wiener index (H′ = 2.24) indicates moderate diversity, characterized by the coexistence of several species and an abundance distribution not strongly dominated by a single taxon. Consistently, the Simpson index (4.85) denotes a low probability of dominance, implying high evenness among species.

Table 6. Results of forest species diversity indices

Index	Value
Shannon - Wiener	2.24
Simpson	4.85
Margalef	5.21

3.4 Cost-benefit ratio (B/C)

The B/C ratio exceeded 1 in all evaluated plots, confirming the economic viability of cocoa-based agroforestry systems (AFS) (Figure 5). The mean B/C value was 2.30, indicating that, on average, returns more than doubled the invested costs. Plot P8 showed the highest B/C value (2.62) and represented the most profitable system, making it a relevant case for identifying replicable management practices. In contrast, plots P1 and P9 (2.06–2.08) exhibited the lowest values, suggesting the need for further diagnosis of yields, costs, or management efficiency. Most plots clustered within a narrow range (2.1–2.3), indicating relatively homogeneous economic performance among production units.

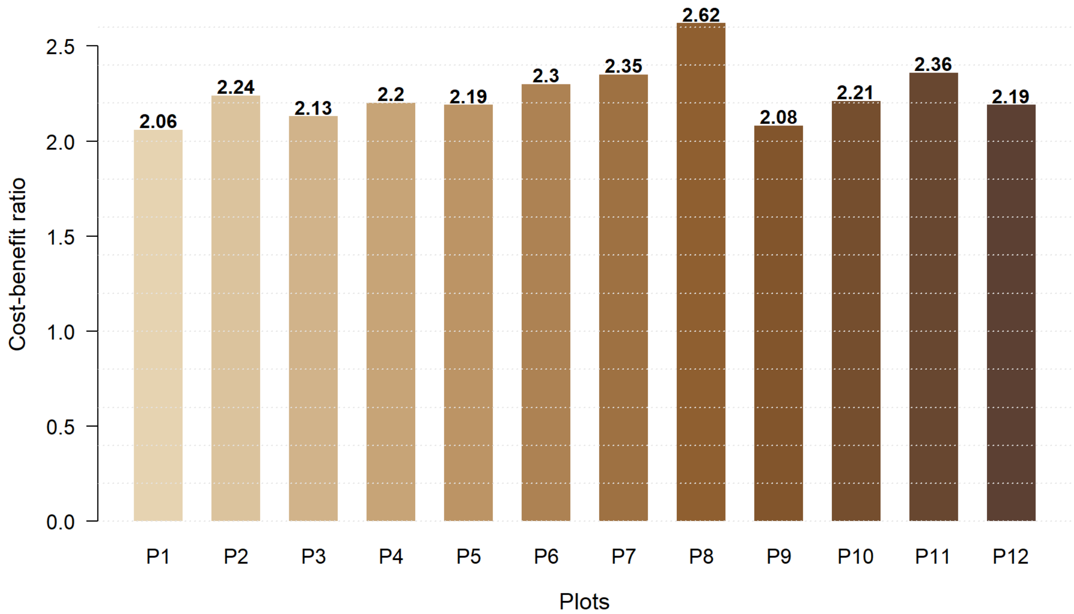

Figure 5. Cost–benefit (B/C) ratio of cocoa-based AFS across the 12 evaluated plots.

3.5 Agronomic and economic correlation of agroforestry systems

The correlation matrix enabled the identification of relationships among soil physicochemical properties, phytosanitary variables, and the economic benefit–cost (B/C) indicator (Figure 6). A perfect positive correlation was observed between organic carbon and organic matter ($r = 1.00$), along with strong positive correlations between these variables and total nitrogen, confirming that soils with higher organic fractions tend to contain greater associated nutrient levels. Soil pH exhibited a weak negative correlation with organic matter ($r = -0.14$), suggesting a slight tendency toward lower organic matter content in more alkaline soils. Similarly, electrical conductivity showed weak negative correlations with available phosphorus ($r = -0.24$) and exchangeable potassium ($r = -0.10$), indicating that increasing salinity may be associated with marginal reductions in nutrient availability.

Phytosanitary variables generally exhibited low correlations with soil chemical properties. Disease incidence showed a moderate positive correlation with potassium ($r = 0.32$), whereas infestation did not display consistent relationships with the evaluated soil variables. Likewise, the economic indicator B/C exhibited weak associations with both soil and phytosanitary variables ($r \leq 0.42$), suggesting that system profitability is not directly driven by the analyzed soil parameters, but rather reflects a combination of management practices, agroforestry system structure, and market conditions.

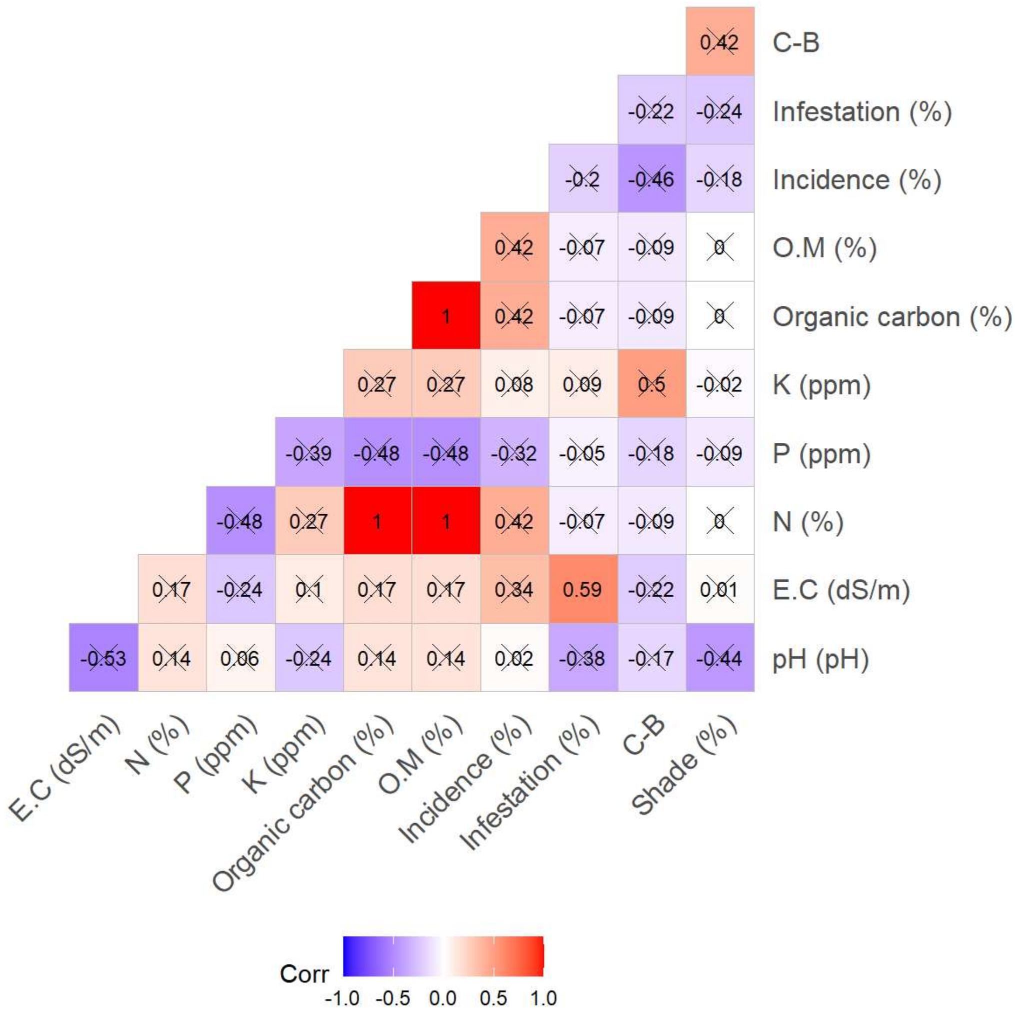

Figure 4. Correlation matrix of edaphic, economic, and phytosanitary variables. Significance at 5% probability; "X" indicates non-significant correlations (p>0.05).

IV. Discussion

Floristic composition and structure of AFS

The cocoa-based AFS evaluated in the province of Utcubamba exhibited a diverse floristic composition, comprising species that perform complementary ecological and productive functions. The predominance of *Calycophyllum spruceanum* and *Laurus nobilis* is consistent with patterns reported for tropical agroforestry systems on Amazonian soils (Suárez et al. 2025) as well as for cocoa plantations in northeastern Peru (Hernandez 2014) and in studies conducted in Bagua and Utcubamba (Goñas et al. 2022), where farmers tend to retain species with high economic value, carbon storage capacity, and contributions to ecosystem stability. Similarly, the presence of high-value species such as *C. spruceanum*, *Cedrela odorata*, *Cordia* spp., and *Musa* spp. widely reported in agroforestry systems in Ecuador (Verdezoto et al. 2023) and the Peruvian Amazon (Vebrova et al. 2013; Goñas et al. 2022), reinforce the role of these systems as important carbon reservoirs and multifunctional landscapes. This pattern is consistent with evidence showing that tree diversity within AFS enhances ecological stability, habitat conservation, and sustainable cocoa productivity (Asigbaase et al. 2019; Tscharntke et al. 2011).

Moreover, the coexistence of fruit trees, timber species, and large canopy trees resembles the structural configurations described by (Beer et al. 1997; Schroth and Harvey 2007), who emphasized that structural heterogeneity promotes both agricultural productivity and biodiversity conservation. The Shannon diversity index (H′ = 2.24) confirms an intermediate level of diversity, which is typical of managed agroforestry systems where farmer-driven selection shapes floristic composition without eliminating structural heterogeneity (Montagnini et al. 2015). Taking together, these floristic patterns highlight the ecological and productive relevance of local AFS and support their potential as sustainable management strategies in Amazonian cocoa landscapes.

Soil properties and functional diversity

The moderate Shannon diversity index value (H′ = 2.24) indicates an intermediate level of tree diversity, characteristic of managed cocoa-based AFS, where selective management practices tend to favor species of productive interest without completely eliminating the structural heterogeneity of the system(Montagnini et al. 2015). The coexistence of fruit and timber species observed in the evaluated plots confirms the multifunctional nature of AFS, which integrate agricultural production with ecosystem services such as improved soil fertility, microclimate regulation, and increased resilience to climate variability (Beer et al. 1997; Schroth and Harvey 2007). This functional diversity contributes to system stability by supporting key ecological processes and reinforcing the long-term sustainability of cocoa cultivation.

Profitability and economic performance of AFS

From an economic perspective, benefit–cost (B/C) ratios greater than 1 across all evaluated plots confirm the profitability of cocoa-based agroforestry systems (AFS) under local conditions in Utcubamba. The mean B/C ratio of 2.30 is consistent with values reported by Ballesteros et al. (2021), who highlighted that traditional cocoa agroforestry systems generate sustainable economic returns when high-value species are integrated and labor use is optimized. The observed variability among plots, with B/C values ranging from 2.06 (P1) to 2.62 (P8), can be attributed to differences in agronomic management, tree density, and soil conditions. This pattern aligns with the findings reported by (Clough et al. 2011; Lahura et al. 2025), who emphasize the role of productive management in shaping economic performance and rural well-being.

Soil correlations, crop health, and productivity

The integration of shade trees into agroforestry systems (AFS) contributes to the creation of microclimates favorable for cocoa cultivation by reducing physiological stress and susceptibility to pests and diseases. In this study, the moderate incidence of pathogens such as *Moniliophthora roreri* and insect pests such as *Monalonion dissimulatum* was associated with tree diversity and canopy structure, supporting the findings of Perfecto and Vandermeer (2008). These positive interactions reinforce the role of agroforestry systems as an effective strategy for climate change adaptation and sustainable crop management (Tscharntke et al. 2011b; Montagnini et al. 2015).

Summary, limitations, and future perspectives

Overall, the results confirm that cocoa-based AFS in Utcubamba constitute sustainable production systems that integrate ecological, economic, and social benefits, consistent with previous findings (Rice and Greenberg (2000); Kellimore (2010)). However, limitations related to the sample size and spatial distribution of the evaluated plots constrain the extrapolation of these results to other cocoa-growing regions with different soil and climatic conditions. In addition, the economic analysis was conducted over a single period and did not account for interannual variability in market prices, input costs, or the occurrence of extreme climatic events.

Future research should therefore incorporate long-term assessments with greater spatial representativeness, as well as evaluating the effects of price volatility and climate extremes on system performance. Strengthening technical assistance, institutional support, and access to financing is also essential for consolidating agroforestry systems as resilient and competitive strategies for sustainable rural development (Ruf and Schroth 2004; Guerra et al. 2025).

V. Conclusion

Cocoa-based AFS in the province of Utcubamba exhibit a diverse floristic composition, comprising species that fulfill complementary productive and ecological functions. The dominance of *Calycophyllum spruceanum* (Benth.) Hook.f. ex K. Schum. and *Laurus nobilis* reflects management decisions oriented toward maximizing economic benefits while maintaining the provision of key ecosystem services, consistent with patterns reported for cocoa agroforestry systems in other tropical regions. The Shannon diversity index (H′ = 2.24) indicates an intermediate level of diversity characteristic of managed AFS, in which the selective retention of useful species shapes plant structure. This diversity contributes to system stability, microclimatic regulation, and the provision of functional habitats, all of which are critical for the agroecological sustainability of cocoa cultivation.

From an economic perspective, benefit–cost ratios greater than 1 across all evaluated plots confirm the profitability of cocoa AFS under local conditions, with a mean value of 2.21, comparable to those reported for traditional cocoa agroforestry systems in other regions. The observed variability among plots (B/C = 2.06–2.62) highlights the influence of factors such as tree density, canopy management, and soil conditions on economic performance. In addition, the presence of shade trees promotes more stable microclimates and reduces cocoa physiological stress, which may help explain the moderate incidence of pests and diseases such as *Moniliophthora roreri* and *Monalonion dissimulatum* Dist. Overall, cocoa-based AFS in Utcubamba integrate ecological and economic benefits and represent a sustainable production strategy whose long-term consolidation requires strengthened technical assistance and improved access to financing to enhance productivity without compromising tree diversity or ecosystem services.

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