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RECEIVED 14 July 2025

REVISED 13 November 2025

ACCEPTED 19 November 2025

PUBLISHED 17 December 2025

CITATION

Gurbillón MÁB, Gomez HS, Angeles WG,
Vigo CN, Ix-Balam MA, Rojas-Briceño NB,
Oliva-Cruz M, Mori Servan DC, Vásquez
Novoa JC, Ramírez CO and
Chappa MY (2025) Sustainability of the cocoa
systems in native communities of the Imaza
district, Amazonas, Peru.
Front. Sustain. Food Syst. 9:1661552.
doi: 10.3389/fsufs.2025.1661552

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Ix-Balam, Rojas-Briceño, Oliva-Cruz, Mori
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Sustainability of the cocoa systems in native communities of the Imaza district, Amazonas, Peru

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Introduction: Cocoa (*Theobroma cacao* L.) production is a key socioeconomic activity for the Awajún Indigenous communities of the Imaza district (Amazonas, Peru), where it represents the principal source of household income. However, limited technical assistance, geographic isolation, and exposure to climate variability create challenges for achieving sustainable production. This study aimed to identify sustainability indicators in cocoa production across economic, social, and environmental dimensions, emphasizing ancestral knowledge and local perceptions of climate change.

Methods: A total of 120 cocoa producers from six Awajún communities (Pakuy, Shushug, Shushui, Shushunga, Uyunsá, and Yangunga) were surveyed using structured questionnaires, field observation, and participatory workshops. Quantitative data were analyzed using ANOVA, Principal Component Analysis (PCA), and Multiple Correspondence Analysis (MCA). Qualitative information was analyzed through thematic content analysis.

Results: Significant differences were found among communities in annual cocoa production (160–770 kg·ha⁻¹·year⁻¹), price per kilogram (8.8–14.7 PEN·kg⁻¹), and access to financial capital ($\chi^2 = 14.37$; $p = 0.013$). PCA revealed that 52.6% of the observed variance was explained by income diversification, market access, and educational level. Communities with irrigation systems and technical assistance (Uyunsá, Pakuy) exhibited greater productivity, whereas isolated communities (Shushug, Yangunga) showed higher vulnerability to climate variability. Traditional practices—such as the use of *Amburana cearensis* and *Cedrela odorata* as shade trees and the burial of organic residues—enhanced agroecosystem resilience.

Discussion: The integration of quantitative sustainability metrics with Indigenous ecological knowledge highlights structural inequalities that influence the sustainability of cocoa systems. The findings emphasize the need for differentiated and intercultural public policies that strengthen technical assistance, access to financial services, and territorial governance.

KEYWORDS

sustainable cocoa, Awajún communities, territorial development, climate change, indigenous agroforestry

1 Introduction

Cocoa production (*Theobroma cacao* L.) represents a strategic economic and social component in various tropical regions of West Africa, Latin America, and Southeast Asia. In 2024, global production exceeded five million tons, with more than 60% concentrated in Côte d'Ivoire and Ghana, the main exporting countries (FAOSTAT, 2025). In Latin America, countries such as Brazil, Peru, Ecuador, and Colombia have managed to position themselves in international markets for fine-flavor cocoa, due to the distinctive attributes of their beans associated with more sustainable cultivation practices, the use of native varieties, and unique sensory profiles (International Cocoa Organization, 2023; Statista, 2025).

Theobroma cacao L. is an agricultural crop of great economic relevance at local, national, and global levels, driven by its use as a primary input in multiple industries, particularly the chocolate sector, which continues to grow, reaching an annual commercial value of several billion dollars (Bagnulo et al., 2023; Beg et al., 2017; Tennhardt et al., 2022). However, its production chain faces persistent environmental, social, and economic challenges, including deforestation, child labor, and the economic vulnerability of small-scale producers. These issues have generated increasing pressure to establish a more ethical and environmentally sustainable supply chain (Mithöfer et al., 2017; Lambin et al., 2018). Although certification mechanisms aimed at promoting responsible practices have been implemented, their capacity to induce structural transformations in the territories of origin remains limited [Ministerio de Desarrollo Agrario y Riego del Perú (MIDAGRI), 2024; Gaia Cacao, 2021].

Peru has established itself as one of the leading exporters of organic and high-quality cocoa, supported by the genetic diversity of its native varieties and the adoption of sustainable agricultural practices. During 2019–2023, cocoa cultivation ranked ninth in terms of contribution to the gross value of national agricultural production, with an estimated annual output of 141.8–166.7 thousand tons, equivalent to 3.3% of the agricultural Gross Domestic Product (GDP) [Ministerio de Desarrollo Agrario y Riego del Perú (MIDAGRI), 2024; Ministerio de Desarrollo Agrario y Riego (MIDAGRI), 2024]. This growth has been driven by favorable public policies, technical assistance programs, and greater access to international markets (Gaia Cacao, 2021). In 2023, the average export price of Peruvian cocoa reached USD 3.17 per kilogram, up 34% year on year, reflecting strong market demand for differentiated-quality products (AgroPerú, 2023).

Agricultural land suitability models applied to Peruvian territory, such as the Analytic Hierarchy Process (AHP) and the Maximum Entropy (MaxEnt) model, have highlighted that the Amazonas region possesses favorable edaphoclimatic and topographic conditions for sustainable cocoa cultivation (Rojas-Briceño et al., 2022). In this region, cocoa production reached 5,501 thousand tons in 2023 (Instituto Nacional de Estadística e Informática (INEI), 2024), positioning it among the country's emerging cocoa-producing regions. This sustained growth has been driven by agricultural promotion programs and by an increasing interest among producers in incorporating high-value crops as a strategy for income diversification. Nevertheless, significant structural limitations persist, including restricted access to specialized markets, deficiencies in infrastructure and postharvest processes, and weak coordination among value-chain actors (Hasan and Karim, 2022). These issues are exacerbated in

remote rural areas, where the State's limited presence hampers the implementation of effective policies for technical assistance, financing, and logistics for small producers (Grupo de Análisis para el Desarrollo (GRADE), 2023; Urteaga and Jesús, 2024; Martín et al., 2023). Moreover, the economic contribution of cocoa is not always clearly reflected in regional GDP, as a large proportion of production is transported and exported through other regions, thereby underestimating its real economic impact (Ministerio de Comercio Exterior y Turismo (MINCETUR), 2024).

The socioeconomic and environmental characterization of cocoa producers is essential for designing inclusive and sustainable development strategies. Moreover, it allows the identification of limitations and opportunities within production systems, as well as a better understanding of the interactions among economic, social, and ecological dimensions that influence the quality of life of cocoa-producing families (Fernández Jeri et al., 2022; Castillo et al., 2023). It also facilitates the formulation of policies aimed at reducing producers' exposure to market volatility and dependence on single buyers' risks, commonly associated with monocropping schemes on smallholder farms (Mithöfer et al., 2017).

Despite advances in promoting cocoa cultivation, there remains a limited understanding of the integral dynamics of the cocoa production system in territories inhabited by the Awajún communities (Somarriba and Harvey, 2002), an Amazonian Indigenous population whose social organization is structured around extended family units and traditional kinship systems. Historically, their subsistence has been centered on activities such as gathering, hunting, fishing, and small-scale horticulture, all developed in harmony with their natural environment (Miranda et al., 2024). In recent years, these communities have progressively engaged in cocoa production as a strategy for economic diversification. However, they face significant limitations in accessing technical assistance, particularly in integrated crop management, due to both geographic barriers and the State's limited presence in remote areas (Carrión and Albert, 2022). The limited understanding of the integral dynamics of cocoa production systems highlights the need to develop participatory, multiscale diagnostics that serve as a foundation for formulating differentiated, culturally relevant, and territorially oriented public policies aimed at sustainability (Carrión and Albert, 2025). In this regard, such strategies should facilitate the valorization of local knowledge, cultural and ecological diversity, and the socioeconomic relationships that structure production systems.

In the Awajún communities of Imaza (Amazonas, Peru), cocoa cultivation has become a key livelihood strategy; however, the lack of technical assistance, limited infrastructure, weak market articulation, and minimal institutional presence constrain the social, economic, and environmental sustainability of their production systems. These limitations perpetuate territorial inequality and hinder the inclusion of Indigenous producers in sustainable value chains. It is hypothesized that the sustainability of cocoa production in the Awajún communities of Imaza is determined by the degree of access to institutional support, adoption of sustainable agricultural practices, and preservation of ancestral knowledge, which together influence economic performance, social organization, and environmental resilience. Therefore, the objective of this study was to identify sustainability indicators of cocoa production in six Awajún communities of Imaza (Amazonas, Peru) across economic, social, and environmental dimensions, emphasizing the role of ancestral knowledge and local perception of climate change.

This research aims to generate scientific evidence to inform the formulation of intercultural, territorially focused policies that promote sustainable rural development and strengthen the resilience of Indigenous cocoa systems.

Consequently, the strategic role of traditional knowledge in the sustainable management of cocoa cultivation is recognized, as cocoa systems managed based on ancestral knowledge demonstrate greater resilience to the impacts of climate change and market fluctuations. Therefore, it is a priority that public policies and development projects recognize this diversity and adapt to the specific characteristics of each territory. However, conventional territorial approaches have tended to overlook social, organizational, environmental, and local perception factors, thereby limiting a comprehensive assessment of the balance between crop profitability and the conservation of ecosystem services that sustain these productive landscapes (Alexander, 2012).

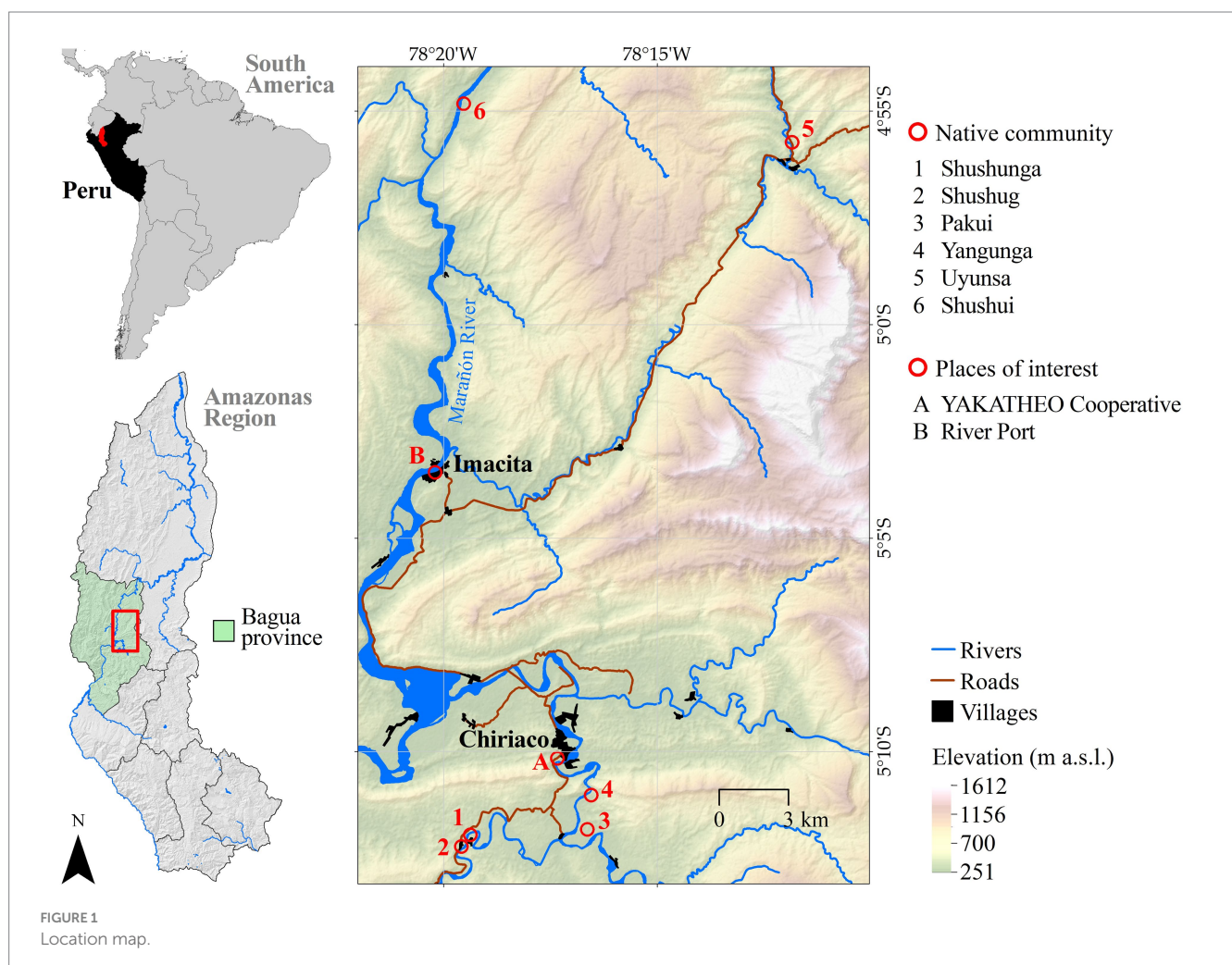
Previous studies on cocoa sustainability have employed participatory and statistical approaches similar to ours. For example, Fernández Jeri et al. (2022) conducted a socioeconomic and environmental characterization of producers in Bagua, Peru, using structured surveys and multivariate analyses; Kouadio et al. (2023) in Côte d'Ivoire evaluated farmers' satisfaction with input credit through regression analysis; and Somarriba and Harvey (2002) in Costa Rica analyzed cocoa agroforestry systems using biodiversity indicators and community

perception. In line with these precedents, our study combines structured surveys and direct observation, integrating statistical analyses ANOVA, Principal Component Analysis (PCA), and Multiple Correspondence Analysis (MCA) to capture both quantitative differences among communities and the diversity of local perceptions of climate change. In this way, the study aimed to address the identified issue: Awajún communities face structural limitations that undermine the sustainability of cocoa production and require differentiated, intercultural policies. Consequently, the objective of this research was to identify sustainability indicators of cocoa production in Imaza (Amazonas, Peru), considering economic, social, and environmental dimensions, with an emphasis on the role of ancestral knowledge and community perception of climate change, thereby providing scientific evidence to guide the formulation of public policies and sustainable territorial development strategies.

2 Materials and methods

2.1 Study área

The research was conducted in the district of Imaza, province of Bagua, Amazonas region, Peru (Figure 1). This district represents one of the main territories of the Awajún people, the second-largest



Amazonian Indigenous group in the country. Imaza has a humid tropical climate, with an average annual temperature of 26 °C and annual rainfall of 1,800–2,300 mm. The altitude ranges from 250 to 600 m a.s.l., favoring cocoa cultivation under agroforestry systems. Six representative Awajún communities were selected: Pakuy, Shushug, Shushui, Shushunga, Uyunsá, and Yangunga. The selection criteria included:

- (i) relevance of cocoa production within the community's economy,
- (ii) accessibility for fieldwork,
- (iii) community willingness to participate, and

Diversity of production conditions (rainfed vs. irrigated, traditional vs. semi-intensive systems).

Each community has between 40 and 80 families and communal territories ranging from 1,000 to 3,500 ha, with 15–25% of land dedicated to cocoa (*Theobroma cacao* L.) production.

2.2 Study design and sampling

A mixed-methods approach was applied, combining quantitative surveys, qualitative participatory tools, and field observation. A sample of 120 producers (20 per community) was determined using stratified random sampling based on family registries provided by local leaders (Apus). This sample size ensured a 95% confidence level and an error margin of $\pm 8\%$. Participation was voluntary, and prior informed consent was obtained in accordance with the ethical guidelines for research with Indigenous communities established by the National University Toribio Rodríguez de Mendoza of Amazonas (UNTRM).

2.3 Data collection

2.3.1 Structured survey

Data collection was carried out using a mixed-methods approach that combined quantitative and qualitative methods (Kouadio et al., 2023). A structured survey was administered to cocoa producers belonging to the native communities of Pakuy, Shushug, Shushui, Shushunga, Uyunsá, and Yangunga (Figure 1). The survey included items related to socioeconomic variables (age, income, access to services), agronomic variables (irrigation systems, fertilization, type of cultivation), environmental variables (waste management, perception of climate change), and social variables (educational level, family structure, community roles). The survey was conducted in person and in Spanish, with local facilitators providing support when necessary to ensure cultural understanding of the questions.

2.3.2 Observation checklist

A direct observation checklist was used in the production plots, allowing for *in situ* validation of agricultural management practices, soil conditions, the presence of shade trees, and postharvest handling. This technique helped contrast the self-reported information producers provided during the surveys with the actual practices implemented in the field, thereby strengthening the validity of the collected data [Kouassi et al., 2023; Instituto Nacional de Estadística e Informática (INEI), 2025].

2.3.3 Participatory workshops

Complementary focus groups were organized in each community to explore local perceptions of climate change, market access, and community organization. Each session gathered 10–12 participants (producers, leaders, and women representatives). Data were systematized using content analysis to identify recurring themes and patterns.

2.4 Data analysis

The sustainability assessment was conducted using a multidimensional framework that integrates economic, social, and environmental indicators. This framework was based on the DPSIR model (Drivers, Pressures, State, Impact, and Response) and adapted to the context of cocoa agroforestry systems. The model allowed the organization of variables into three sustainability dimensions and facilitated the quantitative integration of biophysical and socioeconomic data. Indicators were standardized using z-scores to ensure comparability among variables.

For quantitative variables, the mean and standard deviation were calculated for each of the six native communities. Differences among communities were evaluated using a one-way ANOVA and Tukey's test for multiple comparisons. Prior to analysis, the assumptions of residual normality (Shapiro, Wilk) and homogeneity of variances (Levene) were verified.

Principal Component Analysis (PCA) was used to examine the relationships between quantitative indicators. This technique summarizes information from several related variables into a few new components that explain most of the variation. In this study, PCA highlighted general patterns and identified which variables contributed most to the differences between native communities. Pearson correlations were then calculated to find positive or negative associations between variables.

For categorical variables, multiple correspondence analysis (MCA) was used, which is a technique designed for qualitative data. This allowed us to visualize how the categories of the different variables relate to each other and to the native communities under study. MCA provided a clear picture of how the qualitative attributes were grouped. Chi-square tests were then used to confirm whether these associations were statistically significant.

All calculations were performed using InfoStat/Professional version 2020 (InfoStat, 2025), and PCA figures were generated in R version 4.3.3 (R Core Team, 2025) using the ggplot2 package (Wilkinson, 2005).

3 Results

3.1 Socioeconomic, territorial, and productive characteristics of respondents

The analysis of the social and economic characteristics of cocoa producers from the six native communities revealed substantial differences that directly influence the performance of the production systems. Average ages ranged from 40 to 48 years, with Uyunsá standing out for having relatively younger farmers, which may be associated with recent generational

succession processes or greater openness to new technologies. Regarding family composition, Yangunga and Shushug recorded the highest averages of dependents per household (spouse, children, and other relatives), which could imply greater economic pressure but also a higher availability of labor for agricultural activities. On the other hand, geographic accessibility showed significant contrasts: while Shushui and Uyunsá require approximately 1 h to reach nearby towns, limiting their access to essential services and markets, communities such as Shushunga and Uyunsá are in more favorable locations (adjacent to paved roads), which could facilitate their linkage to institutional or technical networks. Concerning time dedicated to cultivation, data indicated a consistent weekly engagement in farm work across all communities, with slight variations. Shushug stood out for a somewhat greater level of dedication, possibly associated with more intensive cocoa management. Income levels also showed marked heterogeneity. Shushunga and Uyunsá achieved the highest monthly averages, which may reflect better agronomic performance or greater access to differentiated markets. In contrast, producers from Shushug and Yangunga reported the lowest incomes, suggesting the persistence of structural limitations that affect their economic sustainability. These results highlight the need for context-specific intervention strategies that account for the social,

economic, and territorial particularities of each community to strengthen the sustainability of cocoa production systems in rural Amazonian areas.

The main descriptive results for the social, economic, and agronomic variables are presented in Table 1, which shows the means, standard deviations, and significant differences among the six native communities, as determined by Tukey's test ($p \leq 0.05$).

3.2 Multivariate analysis of socio-environmental sustainability in native cocoa-producing communities

3.2.1 Analysis of sociocultural relationships through multiple correspondence analysis (MCA)

We applied Multiple Correspondence Analysis (MCA) to explore associations among categorical variables characterizing the sociocultural profile of the six Awajún cocoa-producing communities. Variables included gender, marital status, education level, land ownership, leadership role (Apu), wife's participation in farm work, and children's school attendance. All variables were coded as nominal factors; data were checked for missing values prior to analysis. Computations were performed in InfoStat/Professional 2020, and plots were generated in R 4.3.3 (*ggplot2*).

TABLE 1 Descriptive statistics of the variables.

Variables	Units	Pakuy	Shushug	Shushui	Shushunga	Uyunsá	Yangunga
Age	Years	47.67 ± 9.39 a	46.27 ± 8.96 a	42.78 ± 15.02 a	45.33 ± 11.63 a	40 ± 10.31 a	47.75 ± 14.98 a
Number of family members	Persons	3.56 ± 0.53 a	5.18 ± 1.33 a	4.11 ± 1.76 a	4 ± 1.32 a	4.67 ± 1.80 a	5.38 ± 2.07 a
Time to the nearest town	Minutes	20.89 ± 18.56 bc	12.55 ± 7.30 c	52.56 ± 8.37 a	49.22 ± 4.66 a	16.44 ± 27.84 c	40.63 ± 14.99 ab
Days per Week Working on the Farm	Days. Week ⁻¹	4.33 ± 0.71 a	5.18 ± 0.75 a	4.33 ± 1.00 a	4.33 ± 1.32 a	4.22 ± 1.20 a	4.50 ± 0.93 a
Monthly Income as a Cocoa Producer	PEN month ⁻¹	622.22 ± 97.18 a	531.82 ± 190.94 a	577.78 ± 139.44 a	700 ± 217.94 a	666.67 ± 282.84 a	500 ± 232.99 a
Monthly income from extra job	PEN month ⁻¹	388.89 ± 310.02 a	100 ± 184.39 b	300 ± 234.52 ab	500 ± 304.14 a	355.56 ± 335.82 ab	275 ± 249.28 ab
Annual Cocoa Production	Kg. ha ⁻¹ .year ⁻¹	221.11 ± 116.99 bc	337.27 ± 93.82 a	160.67 ± 73.95 c	234.89 ± 102.57 bc	770 ± 906.56 ab	249.38 ± 194.47 bc
Price of cocoa per Kg	PEN kg ⁻¹	8.78 ± 0.83 c	9.82 ± 0.40 ab	11.44 ± 5.81 bc	9.44 ± 0.53 bc	14.67 ± 7.70 a	12.75 ± 6.98 abc
Pruning of branches (selective cutting of branches to balance growth, yield, and crop health)	Score 1–3	1.67 ± 0.50 a	2.36 ± 0.50 a	1.44 ± 0.73 a	1.78 ± 0.67 a	2.00 ± 0.87 a	1.88 ± 0.99 a
Pod harvest (action of cutting and collecting mature cocoa fruits to extract the seeds beans).	Score 1–3	1.89 ± 0.60 a	1.91 ± 0.54 a	2.11 ± 0.60 a	1.78 ± 0.67 a	1.78 ± 0.67 a	1.38 ± 0.52 a

Different letters within rows indicate significant differences according to Tukey's test ($p \leq 0.05$).

TABLE 2 Eigenvalues, percentage of variance explained, and cumulative variance of the axes of the Multiple Correspondence Analysis (MCA) for sociocultural variables.

Axis	Eigenvalue	Inertia (Chi ²)	% of variance	Cumulative %
Axis 1	0.47	0.22	12.44	12.44
Axis 2	0.45	0.20	11.32	23.76

The first two MCA dimensions explained 23.76% of total inertia (Dim1 = 12.44%, Dim2 = 11.32%) (Table 2). Axis 1 was defined primarily by education level, leadership, and land ownership, and is interpreted as an axis of social/educational capital and community authority. Axis 2 was driven by family participation in farm activities and children's school attendance, capturing an axis of family dynamics and social cohesion. Accordingly, categories contributing most to Dim1 reflect higher schooling, leadership roles, and land tenure versus lower schooling and lack of tenure; categories contributing most to Dim 2 reflect regular school attendance and shared household

agricultural work versus irregular attendance and limited family participation.

The MCA biplot (Figure 2) shows clear structuring by sociocultural attributes. Pakuy and Shushunga locate toward the quadrant associated with higher education, male leadership (Apu), and land ownership, indicating stronger community organization and social capital. Yangunga and Shushui cluster toward the opposite side, characterized by lower schooling, a higher proportion of women as main farm actors, and irregular school attendance among children. Shushug is positioned near categories of primary education and

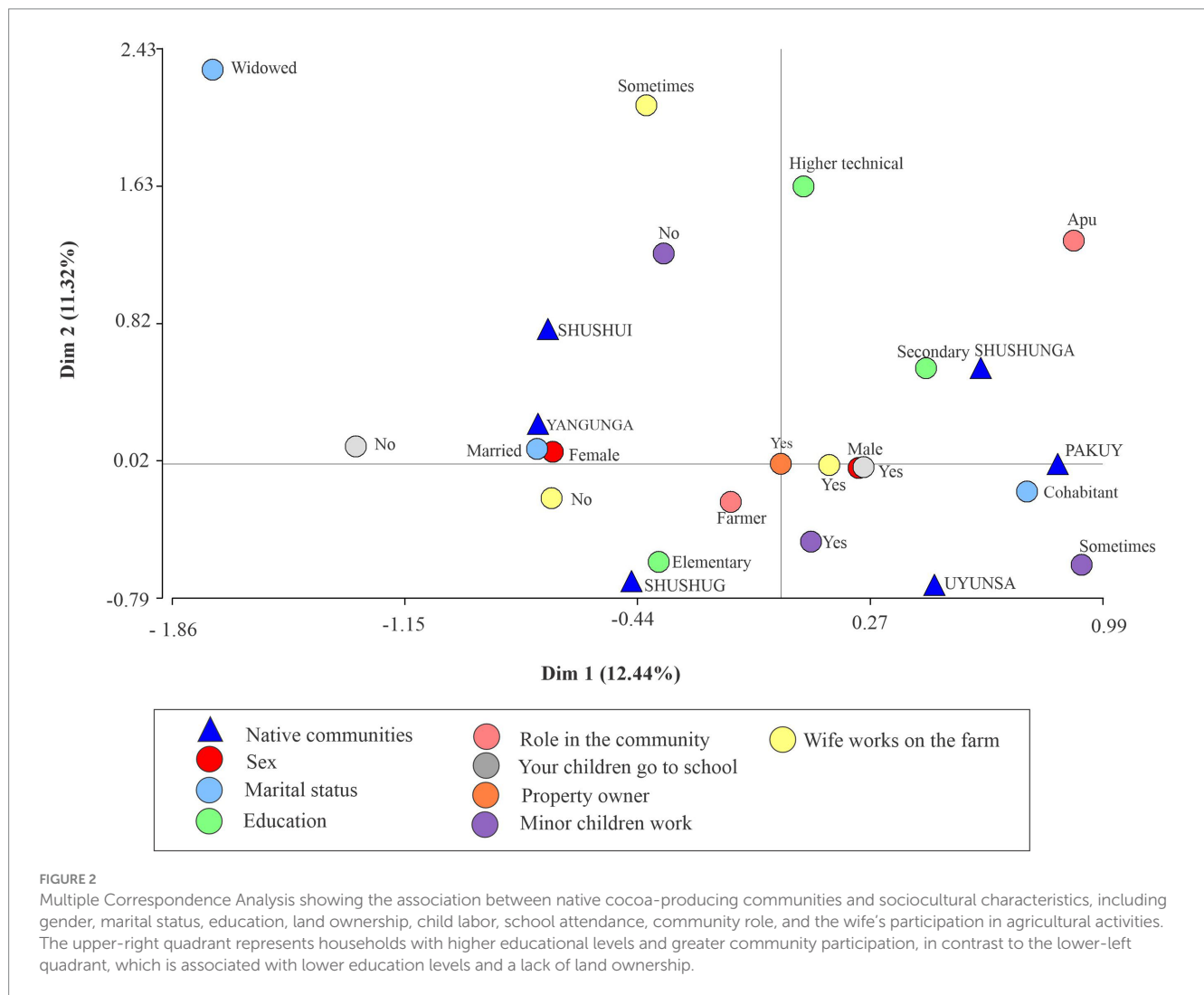


TABLE 3 Coordinates of the native communities on the first two axes of the MCA.

Native community	Axis 1	Axis 2
Pakuy	0.85	−0.003
Shushug	−0.46	−0.69
Uyunsá	0.47	−0.71
Shushunga	0.61	0.56
Shushui	−0.71	0.79
Yangunga	−0.74	0.23

agricultural roles, while Uyunsu displays internal heterogeneity, combining occasional child labor and wives' participation on the farm with regular school attendance. Proximity of points denotes similar category profiles, and greater distances indicate contrasting sociocultural configurations (Table 3).

Conceptually, these results indicate that education, leadership, and land tenure structure Dim1 and differentiate communities with stronger organizational capital, whereas family engagement and schooling structure Dim2 and distinguish households with tighter social cohesion. This sociocultural stratification provides context for later sections by linking social capital and family organization with the sustainability outcomes discussed for each community.

No statistically significant differences were found among the native communities according to the chi-square test of independence for the following variables: gender distribution ($\chi^2 = 1.634$; $p = 0.897$), marital status ($\chi^2 = 14.73$; $p = 0.142$), educational level ($\chi^2 = 8.13$; $p = 0.616$), community role ($\chi^2 = 6.73$; $p = 0.242$), children's school attendance ($\chi^2 = 5.37$; $p = 0.373$), wife's work on the farm ($\chi^2 = 7.66$; $p = 0.662$) and child labor on the farm ($\chi^2 = 16.95$; $p = 0.075$).

3.2.2 Analysis of welfare conditions and institutional assistance through MCA

A Multiple Correspondence Analysis (MCA) was performed to explore relationships between household welfare, access to institutional support, and financial inclusion in the six Awajún cocoa-producing communities. The categorical variables analyzed included *access to financial capital, ownership of household goods, access to health services, vaccination coverage, receipt of technical assistance, and institution providing such assistance*. All variables were coded as nominal factors, and no missing data were detected. The analysis was carried out using InfoStat/Professional 2020, and visualizations were produced in R 4.3.3 (ggplot2).

The first two dimensions explained 39.53% of the total inertia (Dim1 = 24.52%, Dim2 = 15.01%) (Table 4). Axis 1 defined an axis of economic capital and household assets, determined by the availability of financial credit and possession of domestic goods. Axis 2 represented an axis of institutional access and social support, characterized by the presence of health services, vaccination coverage, and technical assistance. Together, these dimensions summarize the socioeconomic inclusion of households and their linkage to public or private support mechanisms.

The MCA biplot (Figure 3) revealed distinct community clusters. Pakuy and Shushunga were located toward the positive side of Dimension 2, characterized by limited institutional assistance and lack of credit access. Yangunga appeared in an intermediate position, reflecting regular health center attendance and vaccination coverage, but absence of financial capital. Shushug, situated in the lower-left quadrant, was associated with credit access from institutions such as Agrobanco, ownership of household appliances, and limited health service coverage. Conversely, Uyunsu and Shushui grouped along the

negative side of both dimensions, defined by the absence of technical and financial support and low asset ownership.

Conceptually, Dimension 1 represents household material well-being, while Dimension 2 reflects the degree of institutional linkage. The proximity of Pakuy and Shushunga indicates similar isolation from financial and technical programs, whereas Shushug stands out as the only community integrated into formal credit networks. This pattern highlights those economic and institutional asymmetries persist among Awajún communities, limiting their capacity to adopt innovations or access sustainable financing. The MCA results emphasize that the sustainability of cocoa production depends not only on productive factors but also on inclusive institutional frameworks that provide both financial and technical support (see Table 5).

No statistically significant differences were detected among communities in years of agricultural experience ($\chi^2 = 4.09$; $p = 0.537$) or family vaccination status ($\chi^2 = 6.396$; $p = 0.270$). In contrast, significant differences were observed in household appliance ownership ($\chi^2 = 27.00$; $p = 0.029$), access to financial capital ($\chi^2 = 14.37$; $p = 0.013$), and the institution providing it ($\chi^2 = 65.11$; $p = 0.0001$). Likewise, significant differences were found in the receipt of technical assistance for cocoa cultivation ($\chi^2 = 26.01$; $p = 0.0001$) and in the institution providing such assistance ($\chi^2 = 21.93$; $p = 0.001$).

3.2.3 Analysis of water management and climate perception through MCA

The Multiple Correspondence Analysis (MCA) was applied to explore associations between water management practices, perception of climate variability, and agroecological adaptation among the six Awajún cocoa-producing communities. The categorical variables analyzed included *type of irrigation system, year-round water availability, presence of shade trees, perception of climate change intensity, perceived relationship between climate change and pest/disease incidence, and production problems attributed to climate variability*. All variables were coded as nominal factors, and the analysis was performed using InfoStat/Professional 2020, with visualization in R 4.3.3 (ggplot2).

The first two MCA dimensions explained 24.35% of the total inertia (Dim1 = 13.26%, Dim2 = 11.09%) (Table 6). Dimension 1 represented an axis of hydrological infrastructure and adaptive capacity, defined by the *type and availability of irrigation systems*. Dimension 2 captured the perceptual and ecological dimension, characterized by farmers' *perception of climate change* and its *association with pest and disease outbreaks*. Together, these dimensions summarize the interaction between physical resources (water management) and cognitive adaptation (climate awareness) within Indigenous cocoa systems.

The MCA biplot (Figure 4) revealed clear patterns among the communities. Pakuy and Uyunsu were positioned toward the positive side of Dimension 1, characterized by permanent irrigation systems

TABLE 4 Eigenvalues, percentage of variance explained, and cumulative variance of the axes of the Multiple Correspondence Analysis (MCA) for household welfare, institutional support, and financial access variables.

Axis	Eigenvalue	Inertia (Chi ²)	% of variance	Cumulative %
Axis 1	0.68	0.46	24.52	24.52
Axis 2	0.53	0.28	15.01	39.53

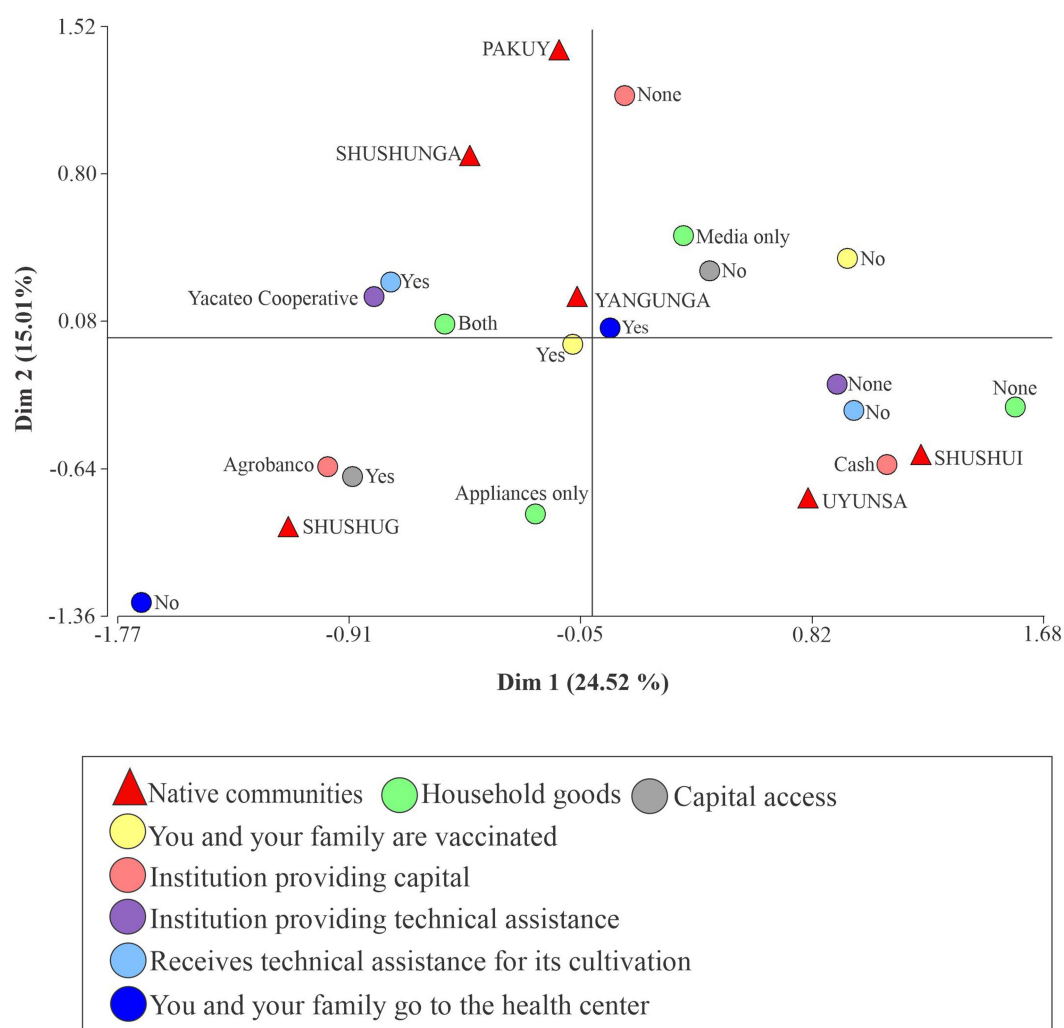


FIGURE 3

Multiple Correspondence Analysis showing the association between native cocoa-producing communities and variables related to access to health services, vaccination, household assets, technical assistance, access to financial capital, and institutional linkages. The upper left quadrant represents communities with better access to financial resources and institutional support, whereas the lower right quadrant groups those characterized by limited credit, scarce technical assistance, and low asset ownership.

TABLE 5 Coordinates of the native communities on the first two axes of the MCA.

Native community	Axis 1	Axis 2
Pakuy	-0.13	1.41
Shushug	-1.14	-0.92
Uyunsá	0.80	-0.78
Shushunga	-0.46	0.89
Shushui	1.22	-0.57
Yangunga	-0.06	0.20

TABLE 6 Eigenvalues, percentage of variance explained, and cumulative variance of the axes of the Multiple Correspondence Analysis (MCA) for water management, year-round water availability, and climate change perception variables.

Axis	Eigenvalue	Inertia (Chi ²)	% of variance	Cumulative %
Axis 1	0.60	0.36	13.26	13.26
Axis 2	0.55	0.30	11.09	24.35

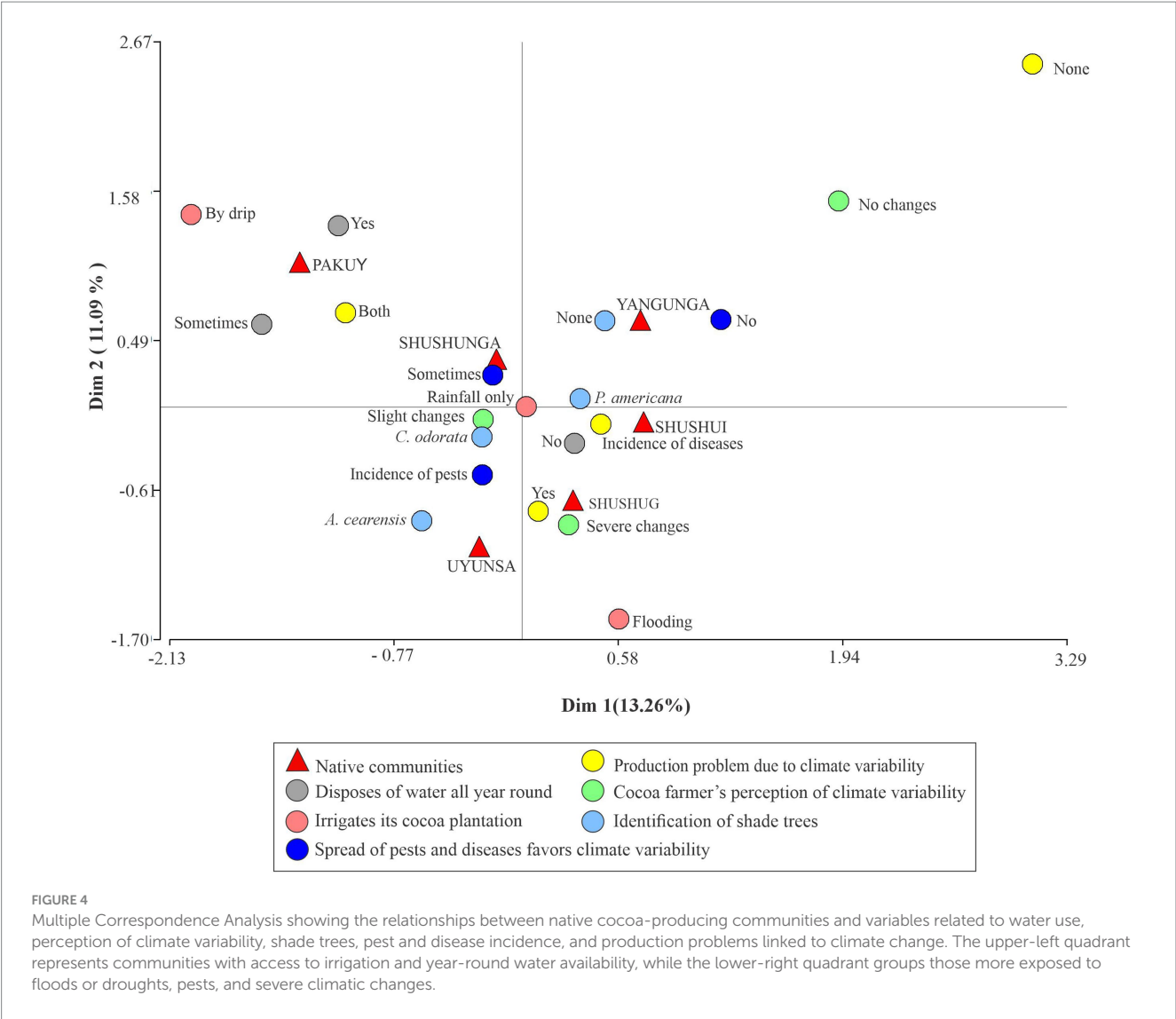


TABLE 7 Coordinates of the native communities on the first two axes of the MCA.

Native community	Axis 1	Axis 2
Pakuy	−1.34	1.06
Shushug	0.31	−0.68
Uyunsa	−0.26	−1.02
Shushunga	−0.15	0.35
Shushui	0.74	−0.11
Yangunga	0.72	0.63

(drip irrigation), use of shade trees such as *Amburana cearensis*, and a strong perception that climate change increases pest and disease pressure. Shushug, located centrally along Dim1, applied flood irrigation and also perceived climate change as severe, directly linked to pest proliferation. In contrast, Shushunga, which relied exclusively on rainfall and used *Cedrela odorata* as a shade species, perceived only slight climatic variations, occasionally related to disease occurrence. Shushui, lacking year-round irrigation and using *Persea americana* for shade, attributed disease problems mainly to climatic shifts, while

Yangunga displayed intermediate perceptions and irregular access to water resources.

In the perceptual map, proximity between points indicated shared practices or beliefs: for example, Pakuy and Uyunsa clustered together due to technified irrigation and high climate awareness, while Shushui and Shushunga grouped around rainfed conditions and moderate climate perception. Conceptually, the MCA results suggest that communities with stable irrigation infrastructure and greater climate awareness exhibit higher

TABLE 8 Eigenvalues, percentage of variance explained, and cumulative variance of the axes of the Multiple Correspondence Analysis (MCA) for agronomic practices, sanitary management, and residue handling variables.

Axis	Eigenvalue	Inertia (Chi ²)	% of variance	Cumulative %
Axis 1	0.62	0.39	17.31	17.31
Axis 2	0.52	0.27	12.11	29.42

adaptive capacity, whereas those dependent on rainfall remain more vulnerable to droughts and pest outbreaks. These findings highlight the importance of integrating water management and climate education in sustainable cocoa production programs for Indigenous territories (see Table 7).

Significant differences were found among communities in the availability of irrigation water throughout the year ($\chi^2 = 25.42$; $p = 0.005$). In contrast, no statistically significant differences were observed for irrigation practices ($\chi^2 = 10.38$; $p = 0.408$), presence of shade trees ($\chi^2 = 20.43$; $p = 0.156$), the perception that climate variability favors pests and diseases ($\chi^2 = 16.98$; $p = 0.075$), perception that climate variability favors pests and diseases ($\chi^2 = 8.13$; $p = 0.616$) production problems attributed to climate variability ($\chi^2 = 8.13$; $p = 0.616$), or perception of climate variability over the past 2 years ($\chi^2 = 13.94$; $p = 0.176$).

3.2.4 Analysis of agronomic and sanitary practices through MCA

The Multiple Correspondence Analysis (MCA) was applied to evaluate the relationships among agronomic practices, crop sanitation, and waste management strategies in the six Awajún cocoa-producing communities. The categorical variables analyzed included type of fertilization (organic, mineral, or none), shade tree cover (none, light, medium, or dense), waste disposal method (burial, burning, or environmental disposal), harvesting of infected pods, use of chemical inputs for pest control, and cultivation method (traditional or organic). All variables were coded as nominal factors. The analysis was performed using InfoStat/Professional 2020, and graphical outputs were generated in R 4.3.3 (ggplot2).

The first two dimensions explained 29.42% of total inertia (Dim1 = 17.31%, Dim2 = 12.11%) (Table 8). Axis 1 represented a gradient of technification and nutrient management, influenced by fertilization practices and methods of waste disposal. Axis 2 defined an axis of sanitary and ecological management, related to the presence of shade trees, handling of infected pods, and use of chemical inputs. Together, these dimensions summarize the contrast between traditional agroforestry practices and incipient technification processes in Indigenous cocoa systems.

The MCA biplot (Figure 5) displayed two clearly differentiated groups. Yangunga and Shushui were located on the negative side of both dimensions, characterized by absence of organic fertilizers, no shade cover, and a preference for burying household and crop residues without collecting infected pods. Shushug and Pakuy, on the other hand, occupied the positive side of Dimension 1, representing organic cultivation systems without mineral fertilization but with residue burning and light tree cover. Finally, Uyunsu and Shushunga were positioned near the center, associated with intermediate shade density, occasional use of organic fertilizers, and sporadic collection of diseased pods.

In the factorial plane, the proximity of Pakuy and Shushug indicates similarity in low-input organic management combined with poor waste control, whereas Yangunga and Shushui form a cluster defined by low intervention and minimal canopy cover. Conceptually, Axis 1 reflects the degree of agricultural modernization and nutrient cycling, while Axis 2 captures ecological resilience and phytosanitary care. The observed distribution suggests that communities with moderate shade management and partial adoption of organic fertilization (Uyunsu, Shushunga) are in a transitional stage toward more sustainable systems. In contrast, Yangunga and Shushui, with limited agroforestry integration, remain more vulnerable to soil degradation and disease recurrence. These results highlight the importance of strengthening training in waste valorization, organic fertilization, and shade management to enhance the agroecological sustainability of Awajún cocoa production systems (see Table 9).

No statistically significant differences were observed among communities in cultivation method ($\chi^2 = 5.27$; $p = 0.384$), use of chemical products for pest and disease control ($\chi^2 = 15.75$; $p = 0.107$), application of organic fertilizers ($\chi^2 = 16.37$; $p = 0.089$), application of mineral fertilizers ($\chi^2 = 7.60$; $p = 0.180$), management of waste and crop residues ($\chi^2 = 17.53$; $p = 0.064$) or shade tree cover ($\chi^2 = 22.12$; $p = 0.105$). In contrast, significant differences were found in the practice of harvesting infected pods ($\chi^2 = 28.19$; $p = 0.002$).

3.2.5 Principal Component Analysis (PCA) based on socioeconomic characteristics

The Principal Component Analysis (PCA) was conducted to summarize the relationships among quantitative variables and identify latent socioeconomic structures differentiating the six Awajún cocoa-producing communities. The variables included age, number of family members, travel time to the nearest town, monthly income from off-farm work, cocoa price per kilogram, and number of cocoa harvests per month (Table 10). All variables were standardized (z-scores) to ensure comparability. The suitability of the dataset for PCA was confirmed through the Kaiser-Meyer-Olkin (KMO = 0.71) statistic and the Bartlett's test of sphericity ($\chi^2 = 168.3$; $p < 0.001$), indicating sufficient inter-variable correlation. The analysis was performed using InfoStat/Professional 2020, with figures generated in R 4.3.3 (ggplot2). Components were extracted by the principal axis method without rotation, and component retention followed the Kaiser criterion (eigenvalues > 1) and visual inspection of the scree plot.

The first two components explained 52.56% of the total variance (PC1 = 29.77%, PC2 = 22.79%) (Table 11). Principal Component 1 (PC1) represented an axis of economic performance and productivity, primarily associated with cocoa price per kilogram, number of cocoa harvests per month, and inversely with household size. Principal Component 2 (PC2) defined an axis of market accessibility and income diversification, influenced by travel time to the nearest town,

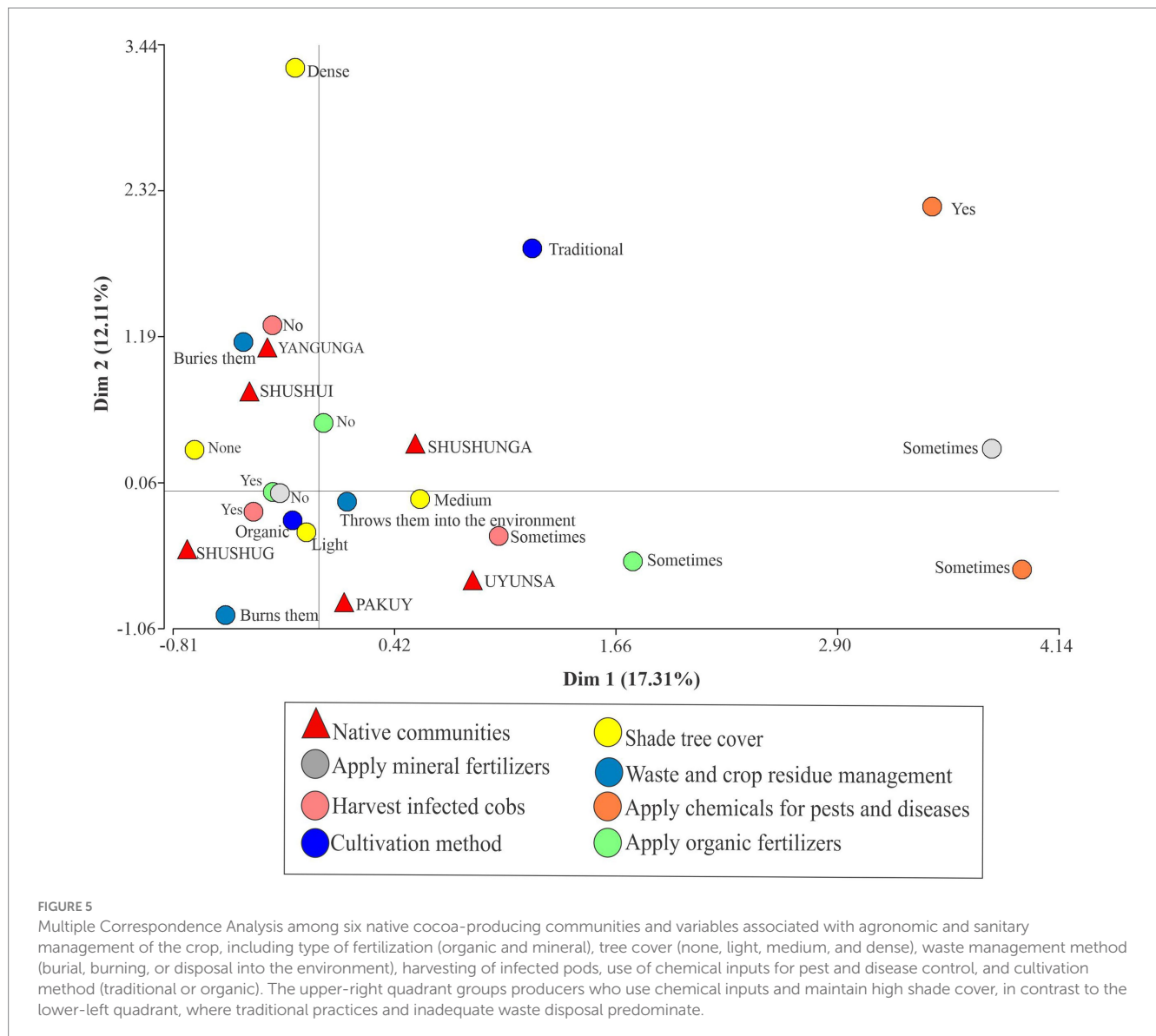


TABLE 9 Coordinates of the native communities on the first two axes of the MCA.

Native community	Axis 1	Axis 2
Pakuy	0.14	-0.86
Shushug	-0.73	-0.45
Uyunsa	0.86	-0.69
Shushunga	0.54	0.36
Shushui	-0.39	0.77
Yangunga	-0.29	1.10

off-farm income, and age of producers. These two components together summarize the contrast between economically dynamic households and those with structural geographic or demographic limitations.

The PCA biplot (Figure 6) showed that Uyunsa and Shushunga were positioned toward the positive end of PC1 and PC2, associated with higher cocoa prices, frequent harvests, and better market connectivity. Conversely, Yangunga clustered at the negative end of

both axes, representing larger households with lower off-farm income and more limited access to markets. Pakuy and Shushug occupied intermediate positions, reflecting transitional profiles between productive and vulnerable conditions. Shushui, located near the centroid, exhibited moderate cocoa prices and minimal diversification of income sources.

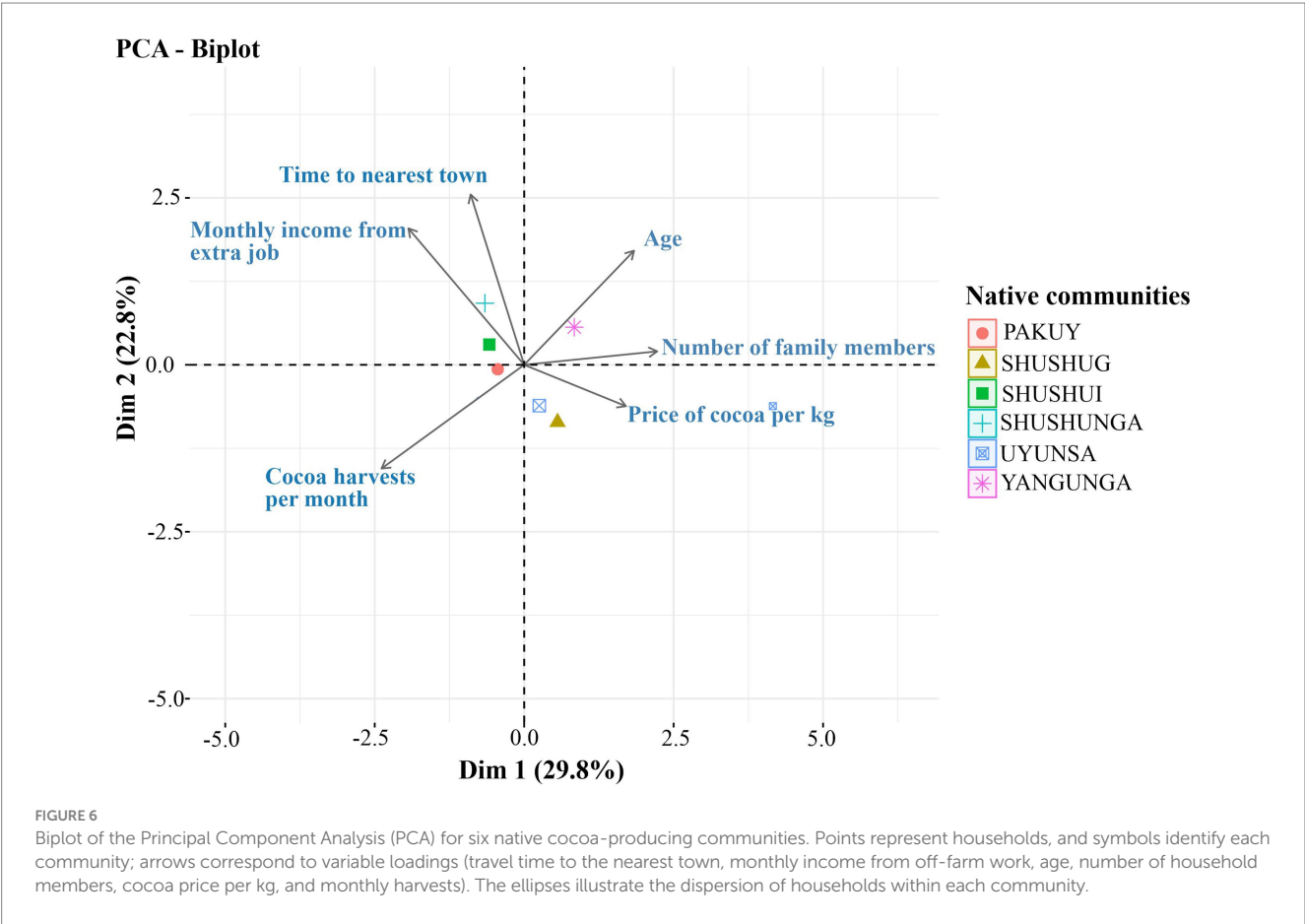
Conceptually, PC1 reflects the economic capital and production intensity that determine household profitability, while PC2

TABLE 10 Loadings and contributions of variables to the first two principal components.

Variable	Loading PC1	Loading PC2	Contribution to PC1 (%)	Contribution to PC2 (%)
Age	0.530	0.493	15.73	17.77
Number of family members	0.642	0.058	23.06	0.25
Time to the nearest town	−0.258	0.736	3.73	39.58
Monthly income from extra job	−0.559	0.589	17.47	25.40
Price of cocoa per Kg	0.491	−0.179	13.50	2.33
Cocoa harvests per month	−0.688	−0.448	26.51	14.68

TABLE 11 Eigenvalues and percentage of variance explained by the principal components (PCA).

Component	Eigenvalue	% of variance	Cumulative %
PC1	1.786	29.77	29.77
PC2	1.367	22.79	52.56
PC3	0.910	15.17	67.72
PC4	0.838	13.96	81.69
PC5	0.649	10.82	92.51
PC6	0.449	7.49	100.00



represents geographical accessibility and labor diversification, influencing adaptive capacity and resilience. The spatial configuration of the biplot highlights that communities closer to

markets and with diversified income sources achieve greater sustainability and economic stability, whereas remote and demographically constrained communities remain more exposed

to vulnerability. These findings reinforce the importance of integrating territorial accessibility, income diversification, and technical support into strategies for sustainable cocoa development in Indigenous territories.

Overall, the multivariate analyses (MCA and PCA) revealed that socioeconomic, institutional, environmental, and agronomic dimensions are deeply interrelated across the six Awajún communities. The combination of these approaches allowed us to identify specific structural patterns ranging from market access and financial inclusion to water management and local perceptions of climate change that jointly explain the variability in cocoa production systems. These findings provide a comprehensive basis for the interpretation and discussion that follows, emphasizing how territorial, social, and cultural factors condition the sustainability of Indigenous cocoa systems in the Peruvian Amazon.

4 Discussion

The results of the multivariate analyses (MCA and PCA) confirmed that the sustainability of cocoa production in the Awajún communities is shaped by the interaction of social, institutional, and environmental dimensions. These patterns reveal that social capital, irrigation infrastructure, and financial inclusion are interdependent drivers of productivity and resilience, supporting the multidimensional approach adopted in this study.

The cocoa production systems encompass diverse production models, ranging from traditional agroforestry schemes with tree cover to intensive monocultures without shade, characterized by the predominance of hybrid varieties and low plant diversity. In particular, agroecosystems that incorporate fruit species contribute to biodiversity conservation and the supply of food and products for self-consumption or local marketing, thereby strengthening the household economy of producers (R Core Team, 2025). Likewise, farmers' perceived satisfaction is closely associated with the performance of their cooperatives, influenced by cognitive and social factors as well as by the demographic and socioeconomic characteristics of their members (Higuchi et al., 2020).

The findings of this study reveal significant territorial inequalities among the Awajún cocoa-producing communities of the Imaza district. Communities such as Pakuy and Shushunga, located in relatively accessible areas, do not receive technical or financial assistance and therefore exhibit a condition of structural isolation. This situation aligns with studies showing that isolated Amazonian communities often lack road infrastructure, electrification, and connectivity key factors for integration into regional or global markets (Bebbington et al., 2018). The situation faced by the Pakuy and Shushunga communities, where no public or private institution provides technical or financial assistance, could limit cocoa productivity. According to previous research, the lack of, or limited access to, technical and financial services in native communities represents a major constraint on innovation and the development of productive capacities, hindering economic inclusion and perpetuating inequality and poverty (Monroy and Hernández, 2008).

The results of the correspondence analysis of sociocultural aspects reflect how these factors influence the social and productive structure of native cocoa-producing communities. The predominance of male producers, landowners, and individuals with secondary education in

the communities of Shushug and Pakuy suggests a more consolidated organizational structure. The presence of the Apu role in these communities appears to be associated with greater participation in communal decision-making processes and better access to productive resources. These are important factors, as social capital, expressed through community leadership, positively influences the adoption of agricultural technologies and enhances communities' resilience to market and climate change challenges (Gul et al., 2023).

When interpreted jointly, the MCA and PCA results suggest that institutional isolation and low educational levels limit the capacity of communities to take advantage of favorable agroecological conditions. Conversely, those with higher social capital and improved irrigation systems show stronger economic performance. This multivariate integration highlights that sustainability gaps in the Awajún cocoa systems are simultaneously social, technical, and territorial.

In the communities of Yangunga and Shushui, where married women predominate working in the fields and having children who do not attend school regularly this pattern suggests that women in these areas are confined to domestic and reproductive roles, with minimal participation in productive activities. This finding is consistent with studies on Indigenous family farming in Latin America (Sulandjari et al., 2023). Furthermore, the limited access to education for children could increase the need to prioritize child labor as a subsistence strategy, a common situation in rural contexts with high poverty levels in Peru (Chachi Montes et al., 2017). The community of Shushug, associated with low educational levels and a lack of land ownership, is at a disadvantage regarding access to productive resources and human capital, as its low level of education limits opportunities for technical capacity building and integration with agricultural initiatives, as observed in rural areas with limited access to training opportunities (Albertus et al., 2020). Finally, the situation in the Uyunsá community is more balanced, as both child labor and occasional participation by wives in agricultural tasks are present, but children regularly attend school. This indicates that the community maintains its traditional practices while simultaneously seeking integration into the formal education systems, which could open opportunities to improve family living conditions in the medium term and facilitate the transition toward sustainable agriculture (Thom et al., 2024; Maini et al., 2021).

The situation of the Pakuy and Shushunga communities, where no public or private institution provides technical or financial assistance, could limit cocoa productivity. According to previous studies, the lack of or limited access to technical and financial services in native communities represents a major constraint to innovation and the development of productive capacities, hindering economic inclusion and perpetuating inequality and poverty within these communities (Kusumastuti et al., 2022; Savira et al., 2025). In the case of Shushug, although it has access to credit, it does not receive technical assistance, which could result in inefficient management of the capital obtained. Access to credit without adequate technical support does not ensure sustained improvements in agricultural production (Kehinde and Ogundéji, 2022).

On the other hand, the communities of Yangunga and Uyunsá have access to health services and vaccination programs; however, their limited access to productive resources may be negatively affecting their living conditions. This is a matter of concern, as the lack of an integrated approach to basic productive, educational, and health services hinders the sustainable development of these communities (Fernández Jeri et al., 2022). The Shushui community, although

receiving economic incentives, lacks access to health services and both technical and financial assistance, reflecting fragmented state intervention and weak territorial coordination among native communities. This situation is perceived as a weakness in programs aimed at implementing sustainable practices to improve cocoa production and the living conditions of these Indigenous peoples, as institutional fragmentation limits the effectiveness of such programs (Salazar et al., 2023; Guest et al., 2023).

The adoption of adaptive agricultural practices, such as crop diversification and the implementation of agroforestry systems, makes cocoa farms more resilient, enabling native communities to cope with changing climatic conditions without compromising agricultural productivity (Ariza-Salamanca et al., 2023). These systems help mitigate the impacts of climate change, particularly in response to rainfall variability and rising temperatures (Pokorny et al., 2021). At the agronomic level, it has been reported that the implementation of good agricultural practices, efficient input use, and participation in at least three annual technical assistance sessions positively influence production efficiency ($p < 0.10$) (Higuchi et al., 2022). Furthermore, studies have shown that cocoa agroforestry systems can achieve greater economic profitability when they integrate environmental services such as carbon sequestration, reinforcing their viability as a sustainable development strategy in Amazonian territories (Goñas et al., 2024). From a comprehensive perspective, the sustainability of the cocoa production systems is determined by a multifactorial interaction involving productivity, edaphoclimatic conditions, market dynamics, and the socioeconomic wellbeing of producers.

The communities of Shushug and Uyunsá clearly recognize that climate change is driving increased pest incidence. However, irrigation practices such as flood irrigation, used in Shushug, may exacerbate the problem, as this type of irrigation promotes excessive humidity that favors the proliferation of insect vectors and pathogens (Goñas et al., 2024). On the other hand, in Uyunsá, the presence of *Amburana cearensis*, a native tree used as shade in cocoa systems, represents whether consciously or not a form of adaptive strategy to climate change, since these trees provide multiple ecosystem services, including soil protection and climate regulation (Kaba et al., 2024; Tham-Agyekum et al., 2023). The Shushunga community perceives that climate change is only occasionally responsible for the spread of diseases. This is a common perspective among native communities, in which climatic variations are often perceived as natural phenomena rather than as part of a broader, more complex problem such as climate change (Varah and Varah, 2022). In contrast, the Pakuy community has more favorable cultivation conditions, including access to year-round drip irrigation. However, it is aware that the increase in pests and diseases is associated with climate change. This awareness may be due to greater understanding and exposure to information on the issue, as documented in studies conducted in more technologically advanced cocoa systems (Lamichhane et al., 2022).

The Shushui community, which lacks irrigation water, associates climate change with increased cocoa disease. The fact that avocado trees are used for shade indicates that tree selection is based on productive use rather than conservation; this mindset may be linked to limited knowledge of climate change mitigation measures (Graefe et al., 2017). The absence of shade trees and the nonuse of organic fertilizers in the Yangunga and Shushui communities suggest production systems with low technical intervention. Nevertheless, good postharvest practices, such as burying crop residues, were found

to reduce the incidence of fruit diseases. This highlights the importance of field phytosanitary hygiene as a strategy to minimize pathogen presence in cocoa systems (Aguilar and Lima, 2018). In contrast, in Shushug and Pakuy, despite organic agriculture, residue burning and limited tree cover were observed to contribute to the loss of organic matter and to create microclimatic conditions that favor the spread of fungal spores (Arévalo-Gardini et al., 2020). This may explain the presence of some infected pods. Regarding the Uyunsá and Shushunga communities, they are in an intermediate situation, with moderate tree cover and occasional use of organic fertilizers. Although these practices provide certain benefits to both the crop and the ecosystem, evidence shows that such agroecological practices are still insufficient, since infected pods were occasionally found. According to various studies, agroforestry systems that combine shade trees with proper soil and residue management reduce pest and disease incidence, enhance crop resilience under unfavorable climatic conditions, and can increase yields by 5 to 15% (Arévalo-Gardini et al., 2020; Fahad et al., 2022).

On the other hand, cocoa production generates significant organic waste, mainly pod husks and other processing by-products, which, if not properly managed, can cause negative environmental impacts. The adoption of sustainable practices such as composting, pellet production, or the application of biochar to the soil helps mitigate these impacts while improving soil physicochemical properties and promoting agroecological management of the production system, thereby generating direct benefits for producer communities (Izurieta-Castelo et al., 2025). The differences observed among communities in variables such as market access (travel time to the nearest town), income from additional work, and harvest frequency are key factors for the sustainability of cocoa agroforestry systems. Communities with better geographic access, more harvests per year, and additional sources of income will be more competitive and sustainable (Cerdeira et al., 2014; Gama-Rodrigues et al., 2021).

The differentiated access to technical assistance, financial services, and infrastructure observed among the Awajún communities clearly indicates that sustainability gaps are not only agronomic but also institutional. Therefore, the results of this study provide critical evidence for designing public policies that strengthen territorial governance and technology transfer in Indigenous areas. It is necessary to promote decentralized technical assistance programs that adapt modern agrotechnological innovations such as precision irrigation, soil fertility monitoring, and digital traceability to the cultural and ecological contexts of native communities. These programs should be developed through intercultural collaboration, valuing ancestral knowledge as a complementary source of innovation. Furthermore, establishing local innovation platforms that connect universities, producer associations, and public agencies could accelerate the cocreation and transfer of adaptive technologies, reducing reliance on external intermediaries. Strengthening the articulation between research institutions, regional governments, and Indigenous organizations would also facilitate continuous training, inclusive financial mechanisms, and gender equity in cocoa value chains. Such actions would translate the findings of this research into concrete policy instruments that enhance resilience, productivity, and environmental stewardship in the Peruvian Amazon, aligning with national objectives for climate adaptation and sustainable rural development. Similar multidimensional patterns have been reported in West African and Southeast Asian cocoa systems,

where social inclusion, credit access, and environmental awareness jointly determine productivity and sustainability.

The ancestral knowledge of the Awajún communities plays a fundamental role in the sustainability of cocoa production systems. This knowledge, transmitted across generations, guides the selection of shade species such as *Amburana cearensis* and *Cedrela odorata*, soil management, and natural pest control through non chemical practices. These actions, rooted in environmental observation and in the Awajún worldview of harmony between forest and crop, constitute local adaptation mechanisms to climate change. Previous studies have shown that agricultural systems managed under traditional knowledge tend to exhibit greater ecological and social resilience, particularly in Amazonian contexts where biodiversity underpins family livelihoods. Recognizing and strengthening this knowledge enables the integration of modern science with Indigenous worldviews, fostering production models that are more sustainable, culturally relevant, and adaptive to climate variability (Varah and Varah, 2022).

5 Conclusion

The study achieved its objective of identifying sustainability indicators for cocoa production in Imaza (Amazonas, Peru), considering economic, social, and environmental dimensions, with an emphasis on ancestral knowledge and perceptions of climate change. Statistical analyses (ANOVA, PCA, and MCA) revealed that the sustainability of the cocoa production system is strongly influenced by territorial, socioeconomic, and governance factors, which create significant disparities among Awajún communities.

Communities with access to modern irrigation systems, technical assistance, and higher levels of education showed better indicators of economic and environmental sustainability. In contrast, the more isolated ones exhibited lower productivity and reduced adaptive capacity to climatic variability. Likewise, traditional practices such as the use of shade trees (*Amburana cearensis*, *Cedrela odorata*) and residue management contributed positively to agroecosystem resilience, reinforcing the importance of local knowledge as a key component of sustainability.

These findings confirm that cocoa sustainability in Indigenous territories depends not only on productive variables but also on the interaction between social capital, ancestral knowledge, and access to institutional services. Therefore, it is recommended to design differentiated, intercultural public policies that integrate adaptive technical assistance with the valorization of traditional knowledge, promote the active participation of Awajún communities in the cocoa value chain, and strengthen territorial governance toward sustainable rural development.

Methodologically, this study demonstrates the usefulness of integrating PCA and MCA within an intercultural sustainability framework, combining quantitative and qualitative dimensions to inform evidence-based policy design for Indigenous territories.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Ethics Committee of the National University Toribio Rodríguez de Mendoza of Amazonas. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MG: Conceptualization, Investigation, Funding acquisition, Writing – review & editing, Supervision, Methodology. HG: Conceptualization, Investigation, Writing – review & editing, Methodology, Writing – original draft. WA: Conceptualization, Validation, Writing – review & editing, Methodology, Investigation. CV: Data curation, Methodology, Software, Writing – original draft, Writing – review & editing. MI-B: Investigation, Supervision, Methodology, Writing – review & editing. NR-B: Writing – review & editing, Data curation, Supervision. MOC: Supervision, Visualization, Funding acquisition, Writing – review & editing. DS: Resources, Investigation, Project administration, Writing – original draft. JN: Investigation, Conceptualization, Visualization, Writing – original draft, Validation. CR: Project administration, Validation, Methodology, Writing – review & editing, Funding acquisition. MYC: Writing – original draft, Formal analysis, Methodology, Writing – review & editing, Data curation, Conceptualization, Investigation.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was funded by the National Council for Science, Technology and Technological Innovation (CONCYTEC) through the PROCIENCIA program, under the call E041-2024-04 titled “Social Sciences Research Project” (Contract No. PE501088338-2024-PROCIENCIA), “Strengthening Socio-Productive Activities of Leading Cocoa-Producing Families in the Imaza district, Amazonas Department.” The project was executed by the Institute for Sustainable Development of the Ceja de Selva (INDES-CES) through the Research Center for Climatology, Renewable Energies, Environmental Technology, and Sustainable Constructions (CINCERCOS) of the National University Toribio Rodríguez de Mendoza of Amazonas, Peru.

Acknowledgments

The authors express their gratitude to the Awajún communities of the Imaza district for their valuable participation and collaboration during the fieldwork. Special recognition is extended to the Yacateo Cooperative for facilitating access to local producers and supporting the implementation of participatory activities. The authors also thank the Research Center for Climatology, Renewable Energies, Environmental Technology, and Sustainable Construction (CINCERCOS), the Institute for Sustainable Development of the Ceja de Selva (INDES-CES), and the National University Toribio Rodríguez

de Mendoza of Amazonas for the technical, logistical, and institutional support provided during the study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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