

Agricultural Sustainability across Altitudinal Gradients: A Multicriteria Assessment of Production Systems in the Andean Region of Southwestern Colombia

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Abstract

Family farming in mountain regions faces critical sustainability challenges due to natural resource degradation, climate change, and socioeconomic constraints. This study assessed the sustainability of 112 agricultural production units in the municipality of Imués, Nariño, Colombia, stratified by altitude — low zone: 1,690–2,200 m a.s.l.; middle zone: 2,200–2,560 m a.s.l.; and high zone: 2,560–3,000 m a.s.l. — and by production system type — monoculture versus polyculture, and with or without livestock. Using a multicriteria approach weighted through Principal Component Analysis (PCA), a General Sustainability Index (GSI) was developed by integrating economic, social, environmental, and technical-productive dimensions. The results revealed significant differences among altitudinal strata ($p < 0.01$), with the middle zone showing the highest GSI (0.68 ± 0.09) and the low zone the lowest (0.52 ± 0.11). Polyculture systems showed greater sustainability than monoculture systems ($p < 0.05$), whereas the presence of livestock did not produce significant differences in the overall GSI. Multiple Correspondence Analysis (MCA) identified three farmer typologies: “traditional highland farmers,” “diversified mid-mountain farmers,” and “extensive low-altitude farmers.” Multiple linear regression models explained 67% of the variance in the GSI ($R^2 = 0.67$), identifying crop diversification, access to formal credit, membership in organizations, and educational level as the main predictors. It is concluded that altitude and production diversification are key determinants of sustainability, underscoring the need for policies differentiated by altitudinal zone.

Keywords: Family farming; multicriteria assessment; principal component analysis; crop diversification; farmer typologies; agricultural credit.

1. Introduction

Family farming constitutes the backbone of food production in the mountainous regions of the Colombian Andes, where more than 80% of production units are managed by peasant families (UPRA, 2021; FAO, 2023). In the department of Nariño, agricultural production spans an altitudinal range from 1,600 to 3,000 m a.s.l., giving rise to a diversity of production systems, climatic conditions, and socioeconomic dynamics that shape the sustainability of the sector (SADER, 2019; Gobernación de Nariño, 2021).

The sustainability of agricultural systems has been widely recognized as a central goal of rural development, integrating economic, social, and environmental dimensions that must be evaluated holistically (Sarandón, 2002; Bossel, 1999). However, assessing sustainability in mountain family-farming contexts poses significant methodological challenges related to the heterogeneity of production systems, data availability, and the need to incorporate indicators that reflect local conditions (López-Ridaura et al., 2002; Astier et al., 2008; Giannetti et al., 2019).

The municipality of Imués, located in the Andean region of Nariño, exhibits characteristics representative of mountain family farming: a predominantly rural population (86.5%), high dependence on agricultural activities, and marked altitudinal stratification that determines the predominant crops (Cerón & Erazo, 2020). This stratification gives rise to distinct production systems: coffee, fruit crops, and panela cane predominate in the low zone (1,690–2,200 m a.s.l.); potato, maize, and bean crops are found in the middle zone (2,200–2,560 m a.s.l.); while milk production, potato, and Andean crops stand out in the high zone (2,560–3,000 m a.s.l.) (Alcaldía de Imués, 2020; Florez Yacual, 2016).

Despite the importance of these zones, territorial planning instruments in the municipality lack adequate updating and fail to incorporate sustainability criteria that would allow rural development to be guided in a differentiated manner (Gobernación de Nariño, 2021). This situation has led to a homogenization of policies and programs that fails to address the particularities of each altitudinal stratum, resulting in unsustainability and resource degradation (Delgado et al., 2007; UPRA, 2018).

Therefore, the objective of this research was to assess and compare the sustainability of agricultural production units across the three altitudinal strata of the municipality of Imués, and to identify the factors that most strongly influence sustainability, in order to generate information that can guide decision-making in rural productive land-use planning.

2. Materials and Methods

2.1. Study site

The study was conducted in the municipality of Imués, department of Nariño, Colombia, located at coordinates 1°3'17" N, 77°29'45" W, with an altitude of 2,560 m a.s.l. at the municipal seat (Alcaldía municipal de Imués, 2004). The municipality covers an area of 86 km² and has a climate

with average temperatures of 15°C, ranging between 7°C and 23°C (Imués, 2020). The rural population accounts for 86.5% of the municipal total (6,440 inhabitants) (Cerón & Erazo, 2020), as shown in Table 1.

Table 1. Altitudinal stratification of the study area, percentage of participation in the study, and main productive activities.

Altitudinal stratum	Altitude (m a.s.l.)	Main crops or productive activities	Identified UPAs*	Sample (n)	Percentage
Low zone	1,690–2,200	Coffee, citrus, and panela cane	144	23	20.5%
Middle zone	2,200–2,560	Potato, maize, bean, and vegetables	180	38	33.9%
High zone	2,560–3,000	Milk production, potato, quinoa, and pastures	401	51	45.5%
Total	—	—	725	112	100%

Note: Author's own elaboration based on data from the Imués Secretariat of Agriculture (2021).

**UPA: Unidad de Producción Agropecuaria (Agricultural Production Unit).*

2.2. Sampling and data collection

The study population consisted of 725 agricultural producers identified by the Imués Secretariat of Agriculture (2021). A stratified probabilistic sampling procedure was applied with a 95% confidence level and a 5% margin of error, yielding a sample of 112 production units, proportionally distributed by altitudinal stratum (Table 1). Producers were selected randomly within each stratum.

Data were collected through structured surveys administered in situ between January and March 2021, using the ODK Collect (Open Data Kit) application to ensure data quality and consistency. Each production unit was georeferenced using GPS. The data collection instrument included questions on social, economic, environmental, and technical-productive variables, based on the methodology of the International Network for Methodology in Farming Systems Research (RIMISP, 1990) and adapted to the local context with validation by a panel of local and academic experts (Berdegúe & Escobar, 1990).

2.3. Selection and calculation of sustainability indicators

A General Sustainability Index (GSI) was constructed from 17 indicators grouped into four dimensions (Table 2), based on the conceptual frameworks of Sarandón (2002) and Flores and Sarandón (2004), together with the methodological adaptations of Belanger et al. (2012) and Thivierge et al. (2014). Indicators were selected considering criteria of relevance, sensitivity, and data availability (Mitchell et al., 1995; Bell & Morse, 1999; Niemeijer & Groot, 2008).

Table 2. Sustainability indicators by dimension

Dimension	Indicator	Description	Unit/Scale
Economic	Income diversification	Number of income sources (agricultural and non-agricultural)	1–4
	Access to formal credit	Access to bank or cooperative credit	1=No, 4=Yes
	Perceived profitability	Perception of system profitability	1–4
	Secure marketing	Stability of marketing channels	1–4
Social	Educational level	Level of formal education	1–4
	Organizational membership	Belongs to a JAC (Communal Action Board), cooperative, etc.	1=No, 4=Yes
	Access to health care	Health service coverage	1–4
	Community participation	Participation in community activities	1–4
Environmental	Soil conservation	Conservation and cover-management practices	1–4
	Crop rotation	Practices rotation and diversification	1–4
	Type of fertilization	Organic, mixed, or chemical	1–4

Dimension	Indicator	Description	Unit/Scale
Technical-productive	Perceived erosion	Perception of erosion on the farm	1–4
	Productive diversification	Number of crops/activities	1–4
	Technical assistance	Access to technical assistance	1=No, 4=Yes
	Pest management	Use of integrated management practices	1–4
	Type of land tenure	Ownership, lease, etc.	1–4
	Type of labor	Family, hired, mixed	1–4

Note: The 1-to-4 scale represents increasing levels of performance for each indicator (1=lowest, 4=highest).

Each indicator was transformed onto a 1-to-4 scale following the coding scheme established in the data collection instrument. Min-max normalization was applied to each indicator to facilitate comparison (Mazziotta & Pareto, 2013; Lira et al., 2002).

2.4. Weighting and aggregation of indicators

Principal Component Analysis (PCA) was used to determine the weights of the indicators within each dimension, following the recommendations of Singh et al. (2009) and Luczak & Just (2021). For each dimension, the first principal component was extracted, and the weights (w_j) were calculated as normalized factor loadings (Eq. 1):

$$w_{ij} = \frac{|\lambda_{ij}|}{\sum_{j=1}^n |\lambda_{ij}|} \quad (1)$$

Where w_{ij} is the weight of indicator i in dimension j , and λ_{ij} is the factor loading of indicator i on the first principal component of dimension j .

Indicators were aggregated through a weighted sum to calculate the Dimension Sustainability Index (DSI_j) and the General Sustainability Index (GSI):

$$ISD_j = \sum_{i=1}^k w_{ij} \cdot I_{ij} \quad (2)$$

$$ISG = \frac{1}{4} \sum_{j=1}^4 ISD_j \quad (3)$$

Where k is the number of indicators in dimension j , and I_{ij} is the normalized value of indicator i .

Additionally, a Synthetic Sustainability Index of Systems (SSIS) was calculated using the approach of Giannetti et al. (2019), based on the 5SEnSU model, which enabled classification of producers into sustainability levels (high, medium, low).

The TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) was applied as an alternative aggregation method to validate the results (Hwang & Yoon, 1981; Luczak & Just, 2021). Euclidean distances to the positive (D^+) and negative (D^-) ideal solutions were calculated as follows:

$$D_i^+ = \sqrt{\sum_{j=1}^m (x_{ij} - x_j^+)^2} \quad (4)$$

$$D_i^- = \sqrt{\sum_{j=1}^m (x_{ij} - x_j^-)^2} \quad (5)$$

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (6)$$

Where S_i is the TOPSIS index for producer i , with values ranging from 0 to 1.

2.5. Data analysis

To identify sustainability patterns and typify producers, Multiple Correspondence Analysis (MCA) was performed using the categorical variables describing production system characteristics (Greenacre, 2007; Cárdenas & Acevedo, 2015). MCA enabled visualization of the relationships between producers and their attributes within a reduced factorial space.

Comparisons of the GSI across altitudinal strata and production system types were conducted using one-way analysis of variance (ANOVA) and Tukey post hoc tests ($\alpha=0.05$), following verification of the assumptions of normality (Shapiro-Wilk) and homogeneity of variances (Levene) (Hair et al., 2019). The Kruskal-Wallis test was used for non-parametric between-group comparisons.

To identify the factors influencing sustainability, a multiple linear regression model was fitted with the GSI as the dependent variable. Predictor variables included producer characteristics (age, education, gender), production system characteristics (crop type, presence of livestock, diversification), and contextual variables (altitudinal stratum, access to credit, organizational membership) (Field, 2018; James et al., 2021). The model was selected using the Akaike Information Criterion (AIC) and validated through 10-fold cross-validation.

Additionally, a Classification and Regression Tree (CART) analysis was applied to identify the cut-off points that best discriminate between sustainability levels (Biau & Scornet, 2016). The tree was pruned using the cost-complexity criterion.

All statistical analyses were performed using R version 4.3.0 (R Core Team, 2023), with the FactoMineR package for MCA, vegan for PCA, MASS for regression, rpart for decision trees, and tidyverse for data manipulation. Plots were generated using ggplot2 and corplot.

3. Results

3.1. General characterization of the production systems

The sample of 112 producers had an average age of 49.3 ± 12.1 years, with a predominance of male producers (68.8%). The predominant educational level was primary education (52.7%), followed by secondary education (26.8%) and higher education (12.5%). Of the producers, 47.3% belonged to some type of organization (JAC, cooperative, etc.).

Regarding production systems, potato was the predominant crop (32.1%), followed by bean (17.0%), maize (13.4%), and coffee (10.7%). Some form of polyculture was practiced by 51.8% of producers, while 48.2% engaged in monoculture. Livestock (mainly cattle) was present in 44.6% of production units.

Table 3. Characteristics of production systems by altitudinal stratum

Characteristic	Low zone (n=23)	Middle zone (n=38)	High zone (n=51)	p-value
Age (years)	47.3 ± 11.8	48.9 ± 12.5	50.3 ± 11.9	0.342
Education (1–4)	2.1 ± 0.8	2.4 ± 0.7	2.0 ± 0.9	0.018*
Polyculture (%)	43.5	60.5	49.0	0.045*
Livestock (%)	30.4	39.5	54.9	0.012*
Technical assistance (%)	39.1	47.4	35.3	0.087
Average area (ha)	2.1 ± 1.2	2.8 ± 1.5	3.2 ± 1.8	<0.001***

Note: Values are presented as mean $\pm$ standard deviation or percentage. Differences were assessed using ANOVA (continuous variables) and chi-square tests (categorical variables).

** $p < 0.05$; *** $p < 0.001$.*

3.2. Weighting and sustainability indices

Principal Component Analysis was used to extract the weights of the indicators within each dimension. The first principal component explained between 45% and 62% of the variance across dimensions. The indicators with the greatest weight in the economic dimension were “income diversification” ($w=0.29$) and “secure marketing” ($w=0.28$); in the social dimension, “educational level” ($w=0.31$) and “organizational membership” ($w=0.27$); in the environmental dimension,

“soil conservation” ($w=0.33$) and “type of fertilization” ($w=0.28$); and in the technical-productive dimension, “productive diversification” ($w=0.30$) and “pest management” ($w=0.26$).

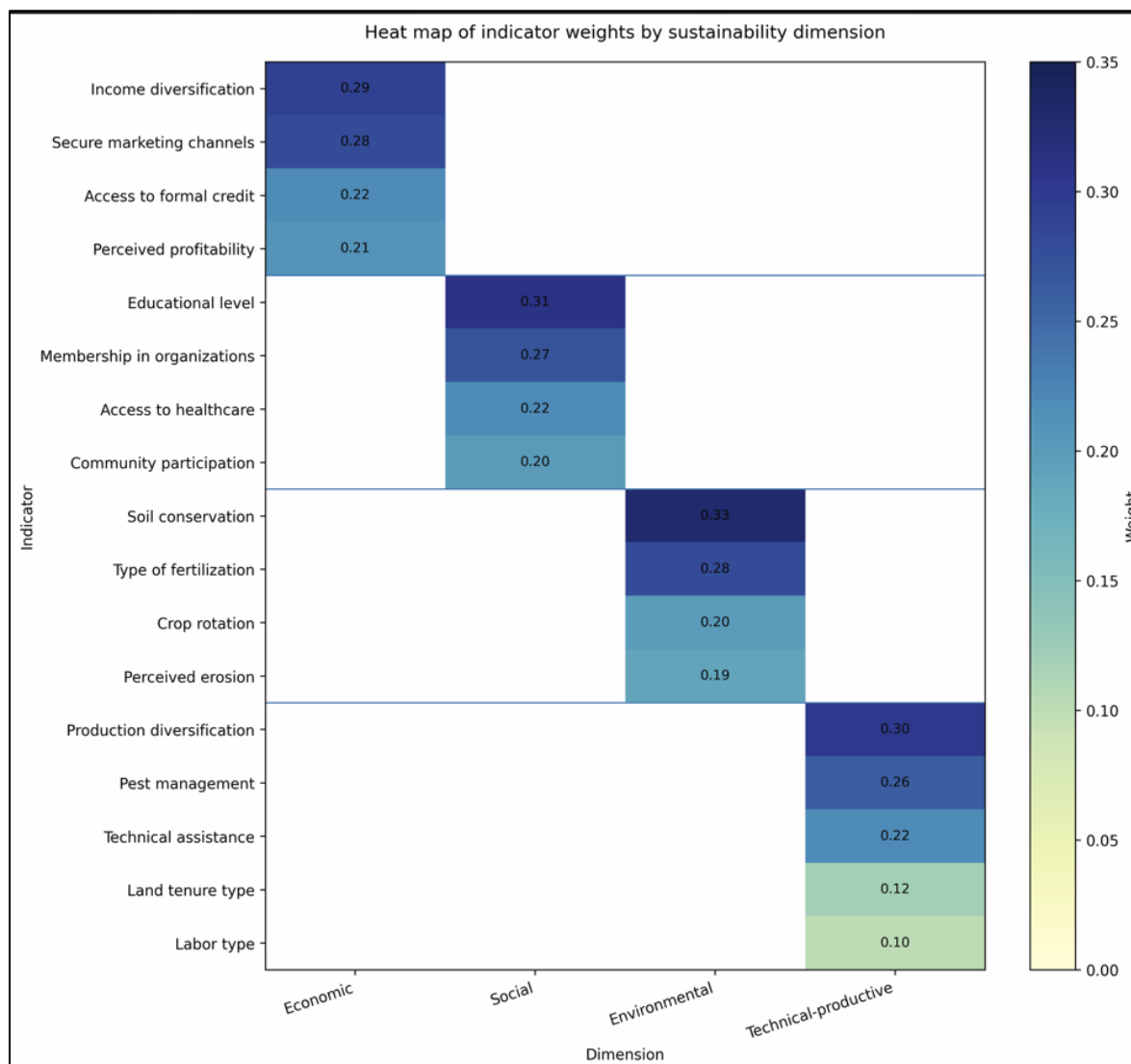


Figure 1. Heat map of indicator weighting by sustainability dimension.

Note: Weights were derived from the first principal component of each dimension. The variance explained was: economic 52.3%, social 48.7%, environmental 57.9%, technical-productive 45.6%.

3.3. Sustainability by altitudinal stratum

The General Sustainability Index (GSI) showed significant differences among altitudinal strata (ANOVA, $F=12.45$, $p<0.001$). The middle zone showed the highest GSI (0.68 ± 0.09), followed by the high zone (0.61 ± 0.11) and the low zone (0.52 ± 0.11) (Figure 2). Tukey post hoc tests revealed significant differences between all pairs of strata ($p<0.05$).

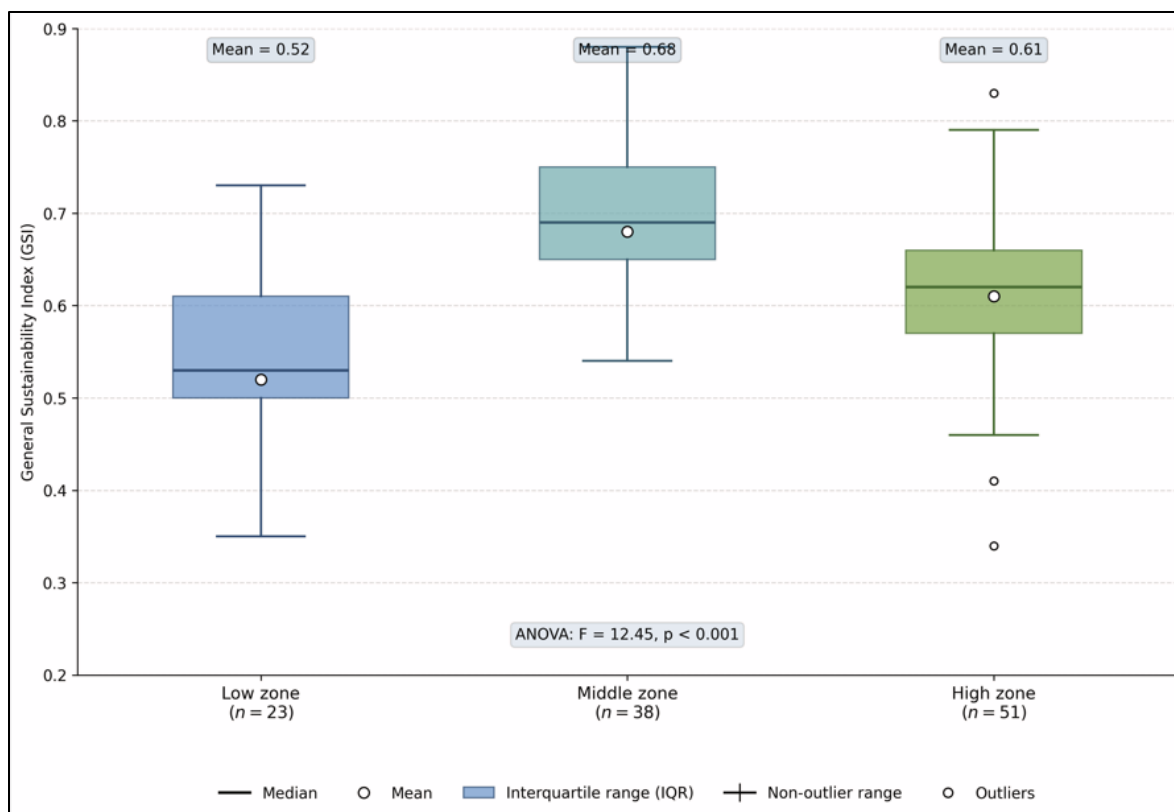


Figure 2. Box-and-whisker plot of the GSI by altitudinal stratum

The diagram shows the distribution of the General Sustainability Index (GSI) across the three altitudinal strata. The middle zone shows the highest median value (0.69), followed by the high zone (0.62) and the low zone (0.53). Dispersion was similar across groups, although the low zone showed greater variability (interquartile range: 0.16 versus 0.12 in the middle zone and 0.14 in the high zone). No extreme outliers were observed in any of the groups. Differences among the three groups were statistically significant (ANOVA, $p < 0.001$), with all post hoc comparisons significant at the $\alpha = 0.05$ level.

Disaggregated analysis by dimension revealed differential patterns (Figure 3). The economic dimension was highest in the middle zone (0.72 ± 0.10) and significantly different from the low zone ($p < 0.001$). The social dimension was highest in the middle zone (0.70 ± 0.11) and lowest in the high zone (0.58 ± 0.12) ($p < 0.01$). The environmental dimension was significantly higher in the high zone (0.68 ± 0.13) than in the low zone (0.49 ± 0.15) ($p < 0.001$). The technical-productive dimension was highest in the middle zone (0.66 ± 0.12) and lowest in the high zone (0.58 ± 0.13) ($p < 0.05$).

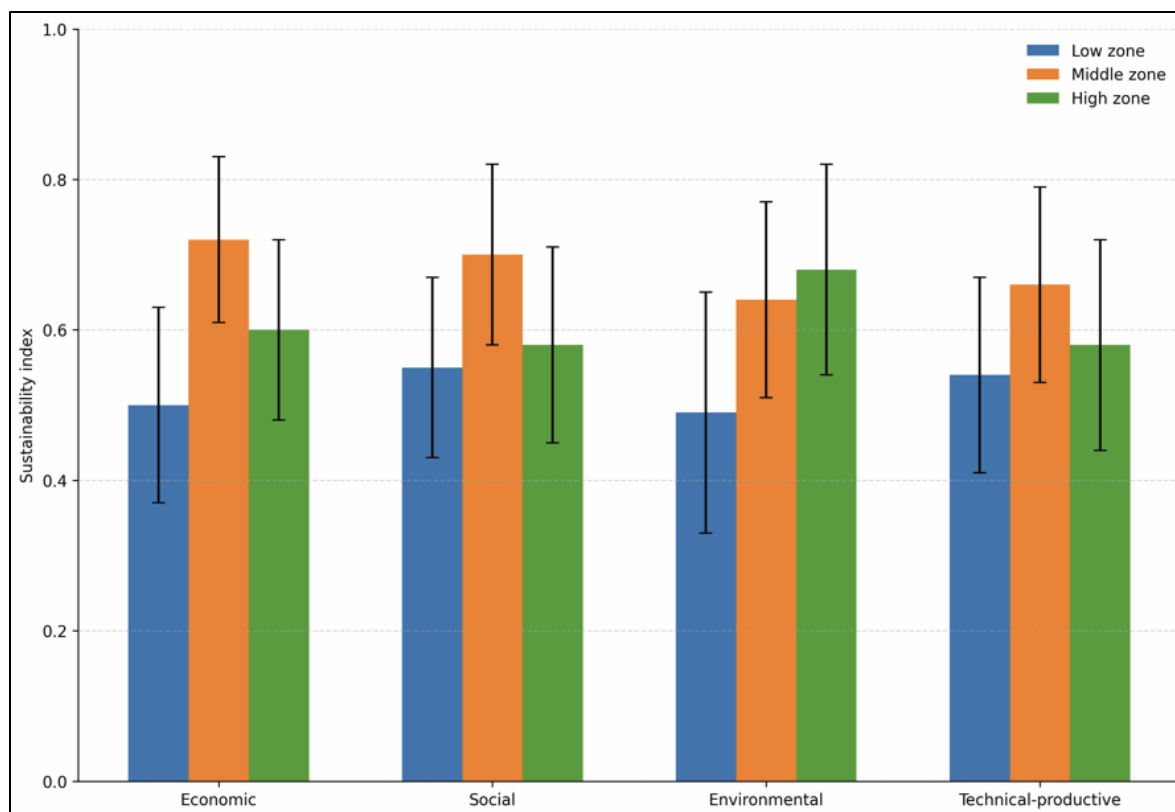


Figure 3. Sustainability indices by dimension and altitudinal stratum

The grouped bar chart shows the sustainability indices for the four dimensions (economic, social, environmental, and technical-productive) across the three altitudinal strata. Bars represent means, and error bars indicate the standard deviation. The middle zone shows the highest bars in the economic and technical-productive dimensions; the high zone stands out in the environmental dimension; and the low zone shows the lowest values across all dimensions, with the environmental dimension being the most critical. The social dimension shows a distinctive pattern, with the high zone presenting the lowest value. Differences are statistically significant for all dimensions (ANOVA, $p < 0.05$ for social and technical-productive; $p < 0.001$ for economic and environmental).

3.4. Sustainability by production system type

Polyculture systems had a significantly higher GSI (0.66 ± 0.10) than monoculture systems (0.58 ± 0.12) ($t = 3.56$, $p < 0.001$). This pattern held across all four dimensions: economic ($p < 0.05$), social ($p < 0.05$), environmental ($p < 0.01$), and technical-productive ($p < 0.01$) (Table 5).

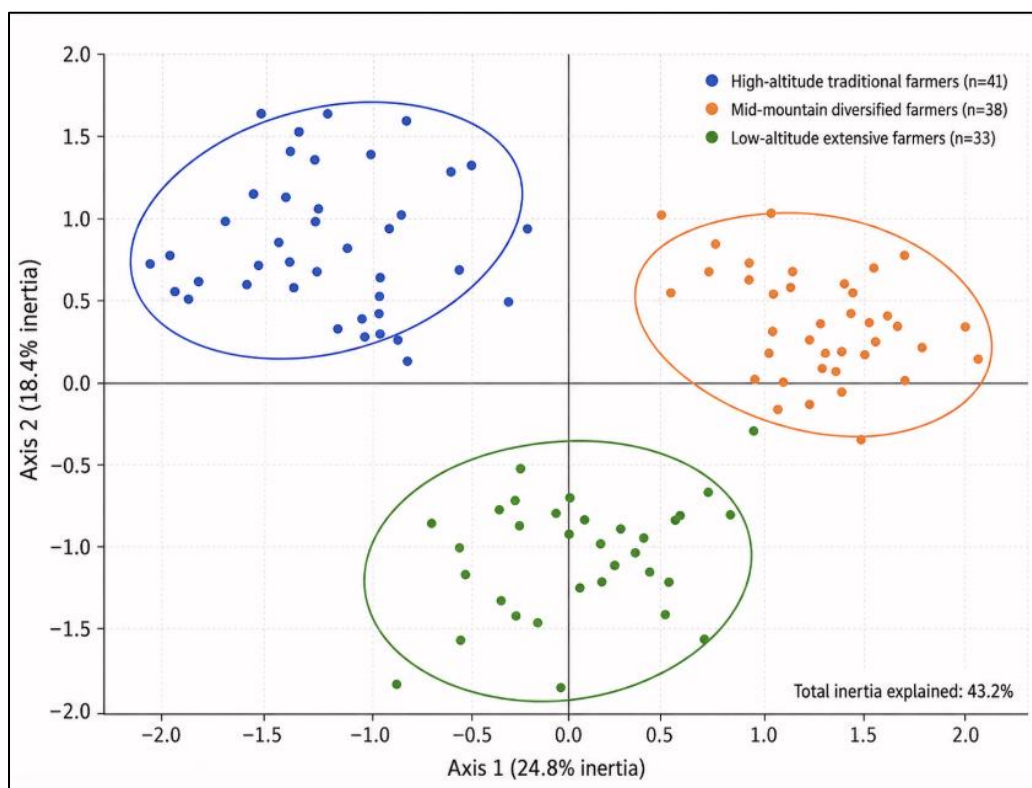
In contrast, the presence of livestock showed no significant differences in overall GSI (with livestock: 0.62 ± 0.11 ; without livestock: 0.61 ± 0.12 ; $t = 0.43$, $p = 0.668$). However, differences were observed in specific dimensions: systems with livestock showed a higher environmental GSI ($p < 0.05$) and a lower economic GSI ($p < 0.05$).

Table 5. GSI by production system type

System type	N	GSI	Economic	Social	Environmental	Technical-productive
Monoculture	54	0.58 ± 0.12	0.55 ± 0.14	0.59 ± 0.13	0.57 ± 0.15	0.56 ± 0.14
Polyculture	58	0.66 ± 0.10	0.63 ± 0.12	0.65 ± 0.11	0.68 ± 0.13	0.66 ± 0.12
p-value		<0.001	0.002	0.008	<0.001	0.001
With livestock	50	0.62 ± 0.11	0.58 ± 0.13	0.62 ± 0.12	0.67 ± 0.14	0.61 ± 0.13
Without livestock	62	0.61 ± 0.12	0.62 ± 0.12	0.63 ± 0.13	0.59 ± 0.14	0.62 ± 0.12
p-value		0.668	0.041	0.382	0.016	0.219

3.5. Producer typology

Multiple Correspondence Analysis (MCA) identified three producer clusters (Figure 4). The total inertia explained by the first two axes was 43.2%.

**Figure 4. Multiple Correspondence Analysis of producers**

The two-dimensional scatter plot shows the projection of the 112 producers onto the factorial plane defined by the first two MCA axes, which explain 43.2% of the total inertia. Points are colored according to cluster membership. Three clearly differentiated groupings are observed: Cluster 1 (light gray circles, $n=41$, “traditional highland farmers”), located in the upper-left region, characterized by low diversification and lower education; Cluster 2 (medium gray circles, $n=38$, “diversified mid-mountain farmers”), in the center-right region, associated with greater diversification and education; and Cluster 3 (dark gray circles, $n=33$, “extensive low-altitude farmers”), in the lower region, related to commercial crops and lower technical assistance. The 95% confidence ellipses for each cluster confirm the separation between groups.

Cluster 1 ($n=41$): “Traditional highland farmers.” Producers from the high zone, with low productive diversification, a predominance of potato monoculture, and extensive livestock. They show the lowest educational level (average 1.8) and low organizational membership (29.3%). Average GSI: 0.58 ± 0.10 .

Cluster 2 ($n=38$): “Diversified mid-mountain farmers.” Producers from the middle zone, with high crop diversification (polyculture in 68.4% of cases), moderate livestock presence (39.5%), and the highest educational level (average 2.6). Greater participation in organizations (55.3%). Average GSI: 0.70 ± 0.08 .

Cluster 3 ($n=33$): “Extensive low-altitude farmers.” Producers from the low zone, with commercial crops (coffee, cane) and lower polyculture (42.4%). Higher average age (51.2 years) and lower access to technical assistance (33.3%). Average GSI: 0.54 ± 0.11 .

3.6. Factors influencing sustainability

The multiple linear regression model for the GSI explained 67.4% of the variance (adjusted $R^2=0.65$, $F=14.82$, $p<0.001$) (Table 6). The predictors with the greatest positive influence were: crop diversification ($\beta=0.24$), access to formal credit ($\beta=0.21$), organizational membership ($\beta=0.18$), and educational level ($\beta=0.16$). Altitudinal stratum (measured as an indicator variable) showed a significant effect, with the middle zone presenting the largest coefficient ($\beta=0.14$).

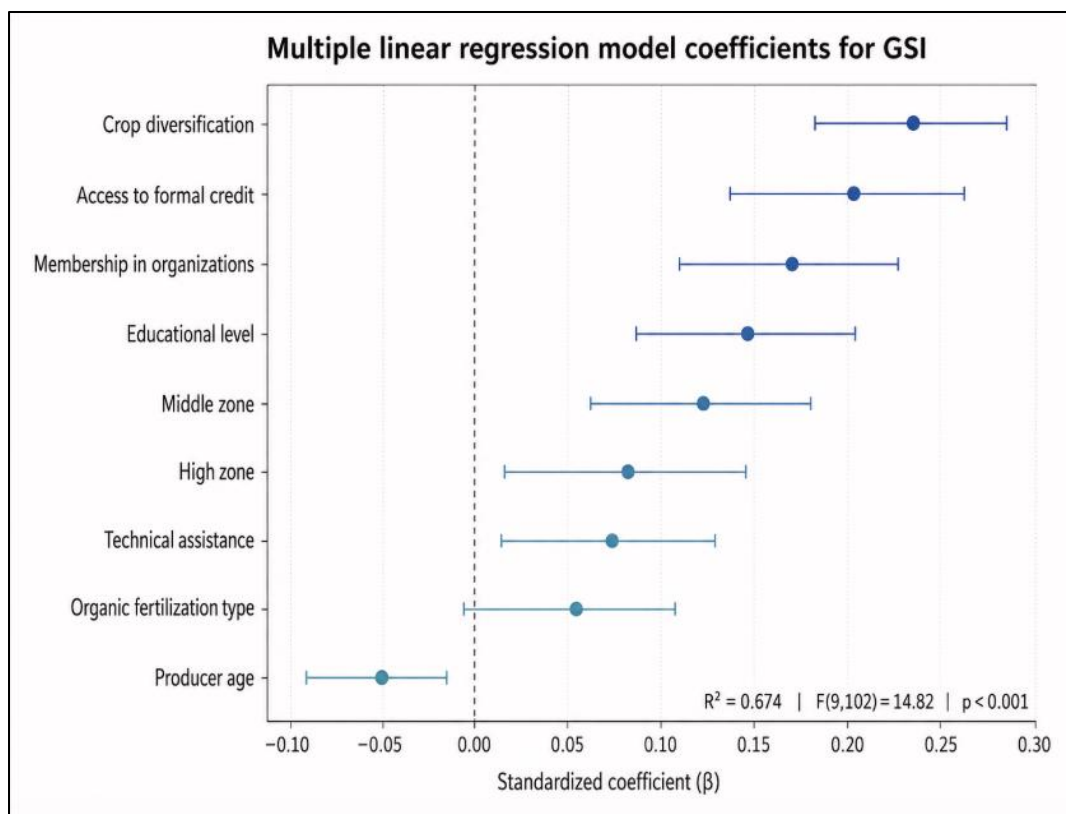


Figure 5. Coefficients of the multiple linear regression model for the GSI

The dot plot shows the standardized coefficients (β) of the predictor variables in the multiple linear regression model, together with their respective 95% confidence intervals. Variables are ordered from largest to smallest coefficient magnitude. Crop diversification ($\beta=0.24$) and access to formal credit ($\beta=0.21$) show the highest coefficients, followed by organizational membership ($\beta=0.18$), educational level ($\beta=0.16$), and middle zone ($\beta=0.14$). Producer age shows a negative coefficient ($\beta=-0.05$), indicating that sustainability decreases with increasing age. All coefficients are statistically significant ($p<0.05$) except for the high zone, which is marginal ($p=0.011$). The confidence intervals do not include zero for any of the significant variables.

Table 6. Multiple linear regression model for the GSI

Variable	Coefficient (β)	Standard error	t	p-value	VIF
(Intercept)	0.21	0.045	4.67	<0.001	—
Crop diversification	0.24	0.034	7.06	<0.001	2.1
Access to formal credit	0.21	0.031	6.77	<0.001	1.9

Organizational membership	0.18	0.028	6.43	<0.001	1.7
Educational level	0.16	0.026	6.15	<0.001	1.6
Middle zone	0.14	0.038	3.68	<0.001	2.4
High zone	0.09	0.035	2.57	0.011	2.1
Technical assistance	0.08	0.029	2.76	0.007	1.5
Organic fertilization type	0.07	0.032	2.19	0.030	1.4
Producer age	-0.05	0.022	-2.27	0.025	1.3

Note: $R^2 = 0.674$, adjusted $R^2 = 0.652$, $F(9,102) = 14.82$, $p < 0.001$. VIF: Variance Inflation Factor.

CART analysis identified crop diversification as the most important predictor for classifying sustainability, with a cut-off point at value 3 (on a 1–4 scale). Other important splitting nodes were access to formal credit and altitudinal zone (Figure 6).

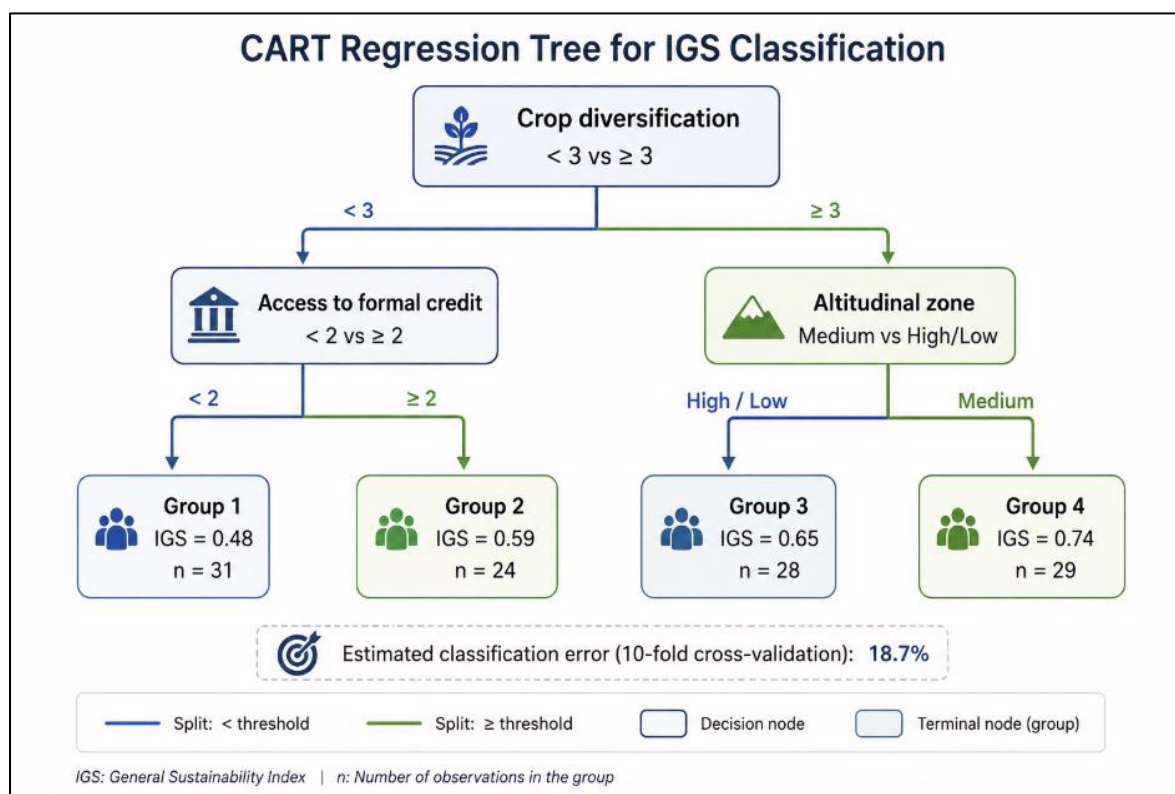


Figure 6. Regression tree (CART) for GSI classification

The regression decision tree shows the hierarchical partitioning rules for predicting the GSI. The root variable is “crop diversification,” with a cut-off point at 3 (on a 1–4 scale). The left node

(diversification < 3) splits on “access to formal credit” (cut-off at 2), while the right node (diversification ≥ 3) splits on “altitudinal zone.” Terminal nodes show the mean GSI value and the number of producers in each group (n). The model identifies four final groups with GSI values ranging from 0.48 (low diversification, no credit) to 0.74 (high diversification, middle zone). The classification error estimated through cross-validation was 18.7%.

The CART model identified the following groups:

- Group 1 (GSI=0.48, n=31): Low diversification (<3) and no access to formal credit.
- Group 2 (GSI=0.59, n=24): Low diversification (<3) with access to formal credit.
- Group 3 (GSI=0.65, n=28): High diversification (≥ 3) in the high or low zone.
- Group 4 (GSI=0.74, n=29): High diversification (≥ 3) in the middle zone.

4. Discussion

4.1. Sustainability across altitudinal strata

The results show a clear differentiation of sustainability among altitudinal strata, with the middle zone presenting the highest GSI. This finding is consistent with previous studies in Andean regions that have documented that intermediate-altitude areas concentrate greater productive diversification and better agroecological conditions for agriculture (SADER, 2019; UPRA, 2021). The lower sustainability observed in the low zone could be explained by greater pressure on natural resources due to the expansion of the agricultural frontier and the intensification of commercial crops (Beltrán-Tolosa et al., 2020), whereas in the high zone, climatic constraints (frost, low temperatures) and reduced access to basic services lower social and economic sustainability (Morton et al., 2023; Zimmerer, 2023).

The environmental dimension showed the largest differences between zones, with the high zone being the most favored. This is likely due to traditional soil conservation practices and lower pressure from intensive land use in these areas (Altieri & Nicholls, 2020; Nicholls et al., 2022). In contrast, the low zone showed the lowest environmental indices, associated with intensive agrochemical use and reduced vegetation cover, a pattern documented in other regions of the Colombian Andes (León-Sicard et al., 2020; Rodríguez-Espinosa et al., 2022).

The difference in the social dimension between strata, with the high zone showing the lowest value, is consistent with the findings of Morton et al. (2023) and Zimmerer (2023), who documented that high-mountain communities face greater challenges in terms of access to basic services, education, and non-agricultural employment opportunities. This situation is compounded by the migration of young people to urban centers, which reduces generational renewal in agricultural activities (Giraldo et al., 2021).

4.2. Productive diversification as a sustainability factor

The finding that polyculture systems exhibit greater sustainability than monoculture systems supports the accumulated evidence on the benefits of agricultural diversification in mountain ecosystems (Gliessman, 2021; FAO, 2023). Crop diversification contributes to income stability, food security, and biodiversity conservation, factors that have been identified as key components of sustainability in family farming systems (Pretty et al., 2020; Giraldo et al., 2021).

The absence of significant differences in overall GSI between systems with and without livestock suggests that livestock production can be a component compatible with sustainability when integrated in a balanced manner with crop production (Mena et al., 2021). However, the lower economic sustainability of livestock systems points to the need to improve the profitability of these systems, possibly through the integration of value-added strategies and access to differentiated markets (Nahed-Toral et al., 2022; García-Barrios et al., 2023).

Polyculture systems showed better outcomes across all dimensions, confirming that diversification is a cross-cutting strategy that strengthens multiple aspects of sustainability (Altieri & Nicholls, 2020). This result is particularly relevant in the context of climate change, where diversification acts as a buffering mechanism against extreme climatic events (Nicholls et al., 2022; Rockström et al., 2023).

4.3. Determinants of sustainability

The regression model identified crop diversification as the most important predictor of sustainability, followed by access to formal credit and organizational membership. These results are consistent with previous studies that have documented the importance of diversification as a resilience strategy in mountain agricultural systems (Morton et al., 2023; Zimmerer, 2023; Anderson et al., 2022).

Access to formal credit emerges as a critical factor for sustainability, consistent with the recommendations of international organizations regarding the need for inclusive financing for family farming (FAO, 2023; World Bank, 2021). Lack of access to credit limits investment capacity for productive improvements and the adoption of sustainable practices, perpetuating cycles of low productivity and environmental degradation (Pretty et al., 2020).

Organizational membership, in turn, facilitates access to services, collective marketing, and resource management, aspects that have been documented as drivers of sustainability in Andean contexts (Giraldo et al., 2021; León-Sicard et al., 2020). Peasant organizations act as spaces for social learning and social capital building, elements that are fundamental for adaptation and innovation in agricultural systems (García-Barrios et al., 2023).

Educational level showed a significant influence on sustainability, confirming that education is a cross-cutting factor that enables the adoption of sustainable practices and the innovation capacity of farmers (Pretty et al., 2020; FAO, 2023; Rockström et al., 2023). Education not only provides

technical knowledge but also strengthens producers' decision-making capacity and self-management (Morton et al., 2023).

The regression tree analysis complemented the findings of the linear model by identifying cut-off points that allow producers to be classified into sustainability levels. The combination of crop diversification and access to formal credit emerges as a simple yet effective criterion for discriminating between sustainability levels, with practical implications for the design of interventions and policies (Anderson et al., 2022; García-Barrios et al., 2023).

4.4. Implications for territorial planning and policy

The findings of this study have direct implications for rural productive land-use planning in the municipality of Imués. Zoning based on sustainability levels suggests that the middle zone could be prioritized for strengthening diversified systems, whereas the low zone would require interventions focused on improving environmental practices and access to credit, and the high zone would need programs to improve the social and economic dimensions (Alcaldía de Imués, 2020).

Differentiation by altitudinal stratum supports the need for differentiated policies that recognize the particularities of each zone, rather than homogeneous approaches that fail to address the specific needs of producers (Gobernación de Nariño, 2021; UPRA, 2021). Promoting diversified systems, access to credit, and the formation of organizations should be central components of rural development policies in the municipality.

The identification of crop diversification as the most important sustainability factor suggests that extension and rural development programs should prioritize strategies that promote productive diversification, such as the implementation of agroforestry systems, crop rotation, and the integration of annual with perennial crops (Gliessman, 2021; Altieri & Nicholls, 2020).

The role of formal credit as a key predictor indicates the need to strengthen rural financial systems and design credit products tailored to the characteristics of family farming (FAO, 2023; World Bank, 2021). This includes microcredit schemes, financing for the adoption of sustainable practices, and guarantee mechanisms that reduce risk for financial institutions.

The influence of organizational membership highlights the importance of social capital for sustainability, suggesting that interventions should include components aimed at organizational strengthening and cooperation networks among producers (Giraldo et al., 2021; León-Sicard et al., 2020).

5. Conclusions

1. The sustainability of production systems in the municipality of Imués shows a significant differentiation among altitudinal strata, with the middle zone (2,200–2,560 m a.s.l.) presenting the highest General Sustainability Index (0.68 ± 0.09), followed by the high zone (0.61 ± 0.11) and the low zone (0.52 ± 0.11), which highlights the need for altitude-

differentiated policies and the importance of considering the agroecological particularities of each stratum in the design of interventions.

2. Polyculture systems show significantly greater sustainability than monoculture systems (0.66 vs. 0.58, $p < 0.001$), with crop diversification being the most important predictor of sustainability ($\beta = 0.24$), followed by access to formal credit ($\beta = 0.21$) and organizational membership ($\beta = 0.18$), confirming that diversification is a key strategy for sustainability in mountain family farming and should be promoted as a central axis of rural development policies.
3. The regression model explains 67% of the variance in the GSI ($R^2 = 0.67$), validating the proposed methodological approach for assessing sustainability using primary data in family-farming contexts, and provides an empirical basis for guiding rural productive land-use planning in the municipality, emphasizing the need to strengthen productive diversification, access to financial services, and peasant organization as pillars of sustainable rural development in the Colombian Andean region.

6. References

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