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Social and Economic Determinants of Technological Adoption in Family Coffee Farming: Implications for Sustainable Territorial Development

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Abstract

Technological adoption in Colombian peasant coffee farming is heterogeneous and subject to multiple socioeconomic and institutional barriers; however, it remains unclear how factors such as education, income, farm size, and rural extension influence this process and territorial sustainability. Therefore, this study aimed to analyze the social and economic determinants of technological adoption in family coffee farming in the village of San Pedro, Piendamó, Cauca, and to explore its tensions with local sustainable development. Using a mixed-methods case study with 42 coffee growers, a Technological Adoption Index (TAI) was applied based on the 12 practices recommended by Cenicafé, together with ordinal logistic regression and principal component analysis. The results showed an average TAI of 48.6%, classified as medium, with an inverse relationship between educational level and adoption: farmers with incomplete primary education reached 38% high adoption, compared with 0% among those with higher education. Technical assistance (OR = 3.06) and access to credit (OR = 1.95) were the strongest predictors, although their coverage remains limited, as only 28.6% of farmers had access to credit. Small farms, under 5 hectares, showed higher adoption and productivity than larger farms, while environmental practices, such as weed management and ecological coffee processing, recorded the lowest adoption rates, below 76%. The study concludes that strengthening participatory rural extension and credit access, as well as reorienting rural education, is a priority to achieve technological adoption that harmonizes productivity and sustainability

Keywords: Technological adoption, family farming, coffee farming, sustainable territorial development, socioeconomic factors.

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1. Introduction

Coffee farming in Latin America is not only an economic pillar for millions of rural families, but also plays a critical role in biodiversity conservation and the shaping of sustainable landscapes (Harvey et al., 2021). However, over the past two decades, coffee production systems have undergone profound transformations driven by international price volatility, climate variability, outbreaks of pests such as coffee leaf rust (*Hemileia vastatrix*) and the coffee berry borer (*Hypothenemus hampei*), as well as demographic and migratory pressures (Bacca et al., 2021; Constantino et al., 2021). In response to this scenario, the adoption of agricultural technologies, ranging from resistant varieties to integrated management practices, has been promoted as a central strategy to increase productivity, reduce costs, and enhance the resilience of peasant livelihoods. Nevertheless, despite institutional efforts, technological adoption in rural territories of countries such as Colombia remains heterogeneous, fragmented, and constrained by multiple socioeconomic, cultural, and educational barriers (Gómez-Castillo & Vargas-Brenes, 2024).

Colombia, as an emblematic producer of mild Arabica coffee, has a globally recognized institutional framework led by the National Federation of Coffee Growers (FNC) and its research center, Cenicafé, as well as an extensive rural extension network. Nevertheless, recent studies show that the transfer of technical and scientific knowledge to small-scale coffee growers faces significant frictions, including discrepancies between experiential knowledge and technical recommendations, mistrust toward extension personnel, and the perception that technical assistance prioritizes productivity indicators over the specific needs and contexts of farming households (Wambua et al., 2021). This tension between the institutional supply of technology and local decision-making processes becomes more pronounced in mountainous hillside territories, where family farming combines coffee, maize, and other food crops, and where producers' living conditions are often precarious (Briones-Ruiz & Juárez-Sánchez, 2021).

In the case of the department of Cauca, particularly in the municipality of Piendamó, the rural settlement of San Pedro constitutes a paradigmatic setting for analyzing this issue. In this area, coffee farming has been practiced for more than 40 years as the main economic activity, under a predominantly peasant-based and small-scale production model. However, the adoption of the twelve agricultural practices formulated by Cenicafé in 1998, designed to reduce production costs and increase yields, has not been homogeneous. While some producers have incorporated technologies such as on-farm seedling production, integrated management of the coffee berry borer, or the application of organic matter, others remain reluctant to adopt practices such as integrated weed management, broadcast fertilization, or increased planting densities. The reasons for this resistance range from costs and lack of credibility to difficulties in understanding technical concepts (Ashadi et al., 2024).

Based on the above, the general objective of this study was to analyze the social and economic factors that influence technological adoption in family coffee farming in the rural settlement of San Pedro, Piendamó, Cauca, as well as to explore the tensions that this process generates in relation to sustainable territorial development. Specifically, the study sought to: (1) characterize the socioeconomic profile of coffee growers and its relationship with the degree of adoption of the 12 agricultural practices; (2) identify the main barriers and facilitators for the implementation of these practices, distinguishing between those aimed at productive efficiency and those with environmental implications; (3) examine coffee growers' perceptions of the role of extension agents and technology transfer mechanisms; and (4) discuss the implications of selective technology adoption for environmental sustainability and the territorial development of the rural settlement.

From a methodological perspective, the study adopted a mixed, exploratory, and descriptive design based on a case-study approach, involving the application of semi-structured surveys to coffee producers in the rural settlement, as well as direct field observation. The technological adoption index was used as the dependent variable, and its relationships with socioeconomic and productive independent variables were explored.

This provides the basis for an analysis that seeks to move beyond the measurement of technological adoption as an end in itself, situating it instead within the broader framework of territorial development dynamics, transformations of rural landscapes, and sustainability challenges in family farming contexts. As recent studies have pointed out, sustainable rural trajectories cannot be imposed from above, but must be built upon the perceptions, priorities, and knowledge of local actors, integrating landscape planning approaches that are both inclusive and transformative (Carvalho & Toledo, 2025).

2. Materials and Methods

The present study was conducted within a mixed-methods, exploratory–descriptive paradigm, using a single case study design (Yin, 2018). This approach was selected because of its suitability for conducting an in-depth analysis of complex social and economic phenomena in which the territorial context—in this case, the rural settlement of San Pedro—plays a decisive role in shaping technological adoption processes. The quantitative component made it possible to measure and correlate socioeconomic variables with the degree of adoption of the 12 agricultural practices, whereas the qualitative component enabled an understanding of coffee growers’ perceptions, barriers, and motivations regarding the technological innovations proposed by Cenicafé.

The study followed a non-experimental, cross-sectional design, as the information was collected at a single point in time, in 2025, without deliberate manipulation of the independent variables.

Study area

The study was conducted in the rural settlement of San Pedro, located in the municipality of Piendamó, department of Cauca, Colombia. This region is characterized by mountainous hillside topography, with elevations ranging from 1,400 to 1,800 m above sea level, agroclimatic conditions suitable for the cultivation of Coffea arabica L., and a coffee-growing tradition spanning more than 40 years. The local economy is predominantly rural, with coffee farming serving as the main source of income and employment. The municipality shows multidimensional poverty indicators above the national average, which adds relevance to the analysis

of technological adoption as a strategy for sustainable territorial development. 133
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Population, sample, and sampling 135

Target population: The target population consisted of all coffee producers 136
in the rural settlement of San Pedro who had been engaged in coffee 137
farming for at least five years and whose household income depended 138
significantly on coffee cultivation. A census population of 78 active pro- 139
duction units was estimated, according to records from the Piendamó 140
Coffee Growers Association and the Departmental Committee of Coffee 141
Growers of Cauca. 142

Sample 143

A non-probabilistic convenience sample was used, complemented by 144
purposive or judgment sampling, selecting coffee growers who met the 145
following inclusion criteria: 146

- Being the owner or tenant, under a valid lease agreement, of the coffee 147
farm; 148
- Having at least five years of experience in coffee cultivation; 149
- Being registered in the technical assistance systems of the Coffee Grow- 150
ers Committee. 151

The final sample consisted of 42 producers, representing 53.8% of the cen- 152
sus population, a statistically representative proportion for case studies in 153
rural development (Hernández-Sampieri & Mendoza, 2018). This sample 154
size is comparable to that used in similar studies in the Latin American 155
region (Gómez-Castillo & Vargas-Brenes, 2024). 156

Study variables 157

Based on the literature and the stated objectives, the following study vari- 158
ables were defined and organized into dimensions: 159

Dependent variables 160

- Technological Adoption Index (TAI): constructed from the number of 161
agricultural practices effectively implemented by each coffee grower, out 162
of a total of 12 practices proposed by Cenicafé (Duque, 2002). The TAI 163
was calculated using the following Equation (1): 164

$$IAT_i = \frac{\sum_{j=1}^{12} P_{ij}}{12} \times 100 \quad (\text{Eq.1})$$
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Where P_{ij} , is a dichotomous variable that takes the value of 1 if producer i has implemented practice j , and 0 otherwise.

Adoption categories: Based on the TAI, coffee growers were classified into four categories (table 1):

Table 1. Classification of coffee growers according to the Technological Adoption Index (TAI).

Category	TAI (%)	Interpretation
None	0%	Does not implement any practice
Low	1%–33%	Implements between 1 and 4 practices
Medium	34%–66%	Implements between 5 and 8 practices
High	67%–100%	Implements between 9 and 12 practices

B) Independent variables (socioeconomic and productive)

Table 2. Independent socioeconomic, productive, and contextual variables included in the analysis.

Dimension	Variables
Coffee grower social characteristics	Age (years); educational level (categories: incomplete primary education, complete primary education, secondary education, technical education, university education); experience (years growing coffee); origin (born in the rural settlement or migrant)
Economic characteristics	Total monthly household income (COP); percentage of income derived from coffee; farm size (ha); land tenure status (owner, tenant, other)
Productive characteristics	Productivity (qq/ha/year); planted varieties; use of technical assistance (yes/no); access to credit (yes/no)
Contextual factors	Perception of the role of the extension agent (5-point Likert scale); perception of environmental sustainability

Data collection instruments

For data collection, a structured questionnaire with mixed-format items was designed and administered. The instrument was divided into five thematic modules:

Module A: Sociodemographic and housing characterization, consisting of 12 closed-ended questions.	182 183
Module B: Productive profile of the coffee grower, consisting of 10 open- and closed-ended questions.	184 185
Module C: Adoption of the 12 agricultural practices, consisting of 12 dichotomous questions, complemented by open-ended questions to identify barriers and motivations.	186 187 188
Module D: Economic aspects and income, consisting of six scale-based and open-ended questions.	189 190
Module E: Perceptions of rural extension and local development, consisting of eight Likert-type statements with five response levels, ranging from “strongly disagree” to “strongly agree.”	191 192 193
<i>Instrument validation: The questionnaire was subjected to the following validation procedures:</i>	194 195
Content validity: Assessed through expert judgment by five specialists: two researchers in rural extension, two agrarian sociologists, and one agricultural economist.	196 197 198
<i>Construct validity: Assessed through exploratory factor analysis (EFA).</i>	199
Reliability or internal consistency: Cronbach’s alpha coefficient was calculated, yielding a value of $\alpha = 0.87$ for the perceptions scale (Module E) and $\alpha = 0.82$ for the barriers scale (Module C). These values are considered indicative of good reliability (George & Mallery, 2019).	200 201 202 203
<i>Data collection was carried out through the following stages:</i>	204
Stage 1. Preliminary reconnaissance and initial contacts, August 2022: Reconnaissance visits were conducted in the rural settlement, along with informal interviews with local leaders and meetings with the Community Action Board, in order to present the objectives of the study and obtain community acceptance.	205 206 207 208 209
Stage 2. Pilot application: The questionnaire was administered to five randomly selected coffee growers to refine the wording of the questions and estimate the average application time, which was 45 minutes per survey.	210 211 212
Stage 3. Systematic fieldwork: Four previously trained surveyors administered the questionnaire on the farms of the 42 selected producers, after obtaining signed informed consent. The surveys were conducted in person and anonymously.	213 214 215 216

Stage 4. Direct observation and field verification: Field visits were conducted on the 42 farms to verify the self-reported adoption of practices, especially those related to the use of cover crops, organic matter, and coffee processing systems, as well as to record photographic evidence of productive and environmental conditions.

The twelve agricultural practices proposed by Cenicafé: technical basis

The 12 practices analyzed in this study correspond to the set of technologies aimed at reducing costs and increasing productivity on coffee farms, developed by the National Coffee Research Center (Cenicafé) since the late 1990s (Duque, 2002). Each of these practices is presented below together with its corresponding institutional technical basis.

Table 1. Agricultural practices for cost reduction and increased production in coffee crop.

No.	Practice	Technical support / Reference
1	Planting of the Castillo variety	Cortina-Guerrero et al. (2012) – Castillo variety, resistant to coffee leaf rust (<i>Hemileia vastatrix</i>); widely adopted after the 2008–2011 epidemics
2	On-farm production of coffee seedlings	Duque (2002) – 62% savings in nursery costs; increased plant adaptation
3	Use of organic matter	Cenicafé (1999) – Use of coffee pulp and compost as nutrient sources; improvement of the physicochemical properties of the soil
4	Increased planting density per hectare	Duque (2002) – Recommendation of 5,000–10,000 plants/ha; alternative use of two seedlings per planting site
5	Integrated Weed Management (IWM)	Hincapié-Gómez and Salazar-Gutiérrez (2007) – Weed control through a combination of mechanical, chemical, and manual practices; 58% cost reduction compared with traditional practices
6	Fertilization based on soil analysis	Duque (2002) – Physicochemical analysis to determine the specific nutritional requirements of each plot
7	Broadcast application of fertilizers	Cenicafé (2007) – Increases fertilizer-use efficiency and reduces labor costs; allows more homogeneous coverage
8	Integrated management of the coffee berry borer (<i>Hypothenemus hampei</i>)	Bustillo et al. (2016) – Combination of cultural control, including timely harvesting, biological control using <i>Beauveria bassiana</i> , and chemical control
9	Renewal through stumping	Duque (2002) – Total or selective cutting technique of coffee plants to induce regrowth; renewal cycle every 7–8 years
10	Exclusive harvesting of ripe coffee cherries	Cadena-Gómez (2005) – Sampling indicates that 15% of the harvest corresponds to green or overripe cherries, affecting sensory quality
11	Ecological coffee processing	Roa et al. (1999) – Reduces water consumption by 98%, decreases wastewater generation, and enables the recovery of coffee pulp as fertilizer or animal feed

12	Food production within coffee plantations	Farfán-Valencia (2007) – Agroforestry systems with plantain, maize, and fruit trees; income diversification and improved food security
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Statistical data analysis 230

Data analysis was carried out in three complementary phases using IBM SPSS Statistics, version 29; RStudio, version 4.3, with the tidyverse, factoextra, and nnet packages; and JASP, version 0.18, for the verification of selected models. 231
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Descriptive statistics 235

Measures of central tendency, including the mean and median, and measures of dispersion, including the standard deviation and interquartile range, were calculated for continuous variables. For categorical variables, absolute and relative frequency distributions were estimated. The results are presented through contingency tables and bar charts. 236
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Inferential statistics 241

To explore the associations between the independent variables and the Technological Adoption Index (TAI), several statistical tests were applied according to the nature of the variables and the assumptions of each model. Associations between categorical variables, such as educational level and adoption category, were assessed using the chi-square test of independence (χ^2), provided that more than 80% of the cells had expected frequencies equal to or greater than five. Differences in mean TAI values between two groups, for example according to access to credit, were examined using Student's t-test for independent samples, after verifying normality with the Shapiro–Wilk test and homogeneity of variances with Levene's test. When comparing mean TAI values across more than two groups, such as income ranges, one-way analysis of variance (ANOVA) was used, followed by Tukey's honestly significant difference (HSD) post hoc test, under the assumptions of normality, homoscedasticity, and independence. Finally, correlations between continuous variables, such as age, farming experience, and TAI, were analyzed using either Pearson's or Spearman's correlation coefficient, depending on the distribution of the data, while considering linearity and the absence of influential outliers. 242
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Multivariate predictive modeling 260

Given the complex and multidimensional nature of technological adoption, an ordinal logistic regression (OLR) model, or ordered probit model, was fitted to estimate the probability of belonging to a given adoption category—low, medium, or high—as a function of a set of socioeconomic and productive predictors. 261
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The general equation of the model was:

$$\text{logit}(P(Y \leq j)) = \alpha_j - (\beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k) \text{ (Eq.2)}$$

Where:

Y = adoption category, where 1 = low, 2 = medium, and 3 = high;

α_j : represents the cut-off points or thresholds;

β_k : represents the regression coefficients associated with each predictor variable X_k

The predictor variables included in the model were educational level, total monthly income, age, farming experience, farm size, access to credit, technical assistance, and perception of the extension agent. Model goodness of fit was assessed using the likelihood ratio test, McFadden's pseudo- R^2 , and the Brant test to verify the proportional odds assumption.

Principal component analysis (PCA)

As a complementary dimensionality reduction technique, principal component analysis (PCA) was applied to identify underlying groupings among the 12 agricultural practices and to synthesize the information into a reduced number of factors or latent dimensions. The extraction criteria considered were an eigenvalue greater than 1 and cumulative explained variance equal to or greater than 70%. Sample adequacy was verified using the Kaiser–Meyer–Olkin measure, with $KMO > 0.60$, and Bartlett's test of sphericity, with $p < 0.05$.

3. Results

Socioeconomic characterization of the sample

The sample consisted of 42 coffee growers from the rural settlement of San Pedro, Piendamó, Cauca. Table 2 presents the main sociodemographic and economic characteristics of the respondents.

Table 2. Socioeconomic characterization of the surveyed coffee growers (n = 42).

Variable	Category / Value	Frequency (%) or Mean (SD)
Age (years)	Mean (SD)	46.3 (11.2)
Educational level	Incomplete primary education	52.4%
	Complete primary education	26.2%
	Secondary education	14.3%
	Technical/university education	7.1%
Experience in coffee farming (years)	Mean (SD)	23.8 (12.5)
Farm size (ha)	Mean (SD)	4.6 (6.1)
	0.5–5.0 ha	71.4%
	5.1–20 ha	19.0%
	>20 ha	9.6%
Monthly household income (COP)	Mean (SD)	687,000 (312,000)
	Below one legal monthly minimum wage*	83.3%
Land tenure	Owner	76.2%
	Tenant	23.8%
Access to agricultural credit	Yes	28.6%
Technical assistance	Yes, Coffee Growers Committee	76.2%
	Does not receive or is unaware of it	23.8%

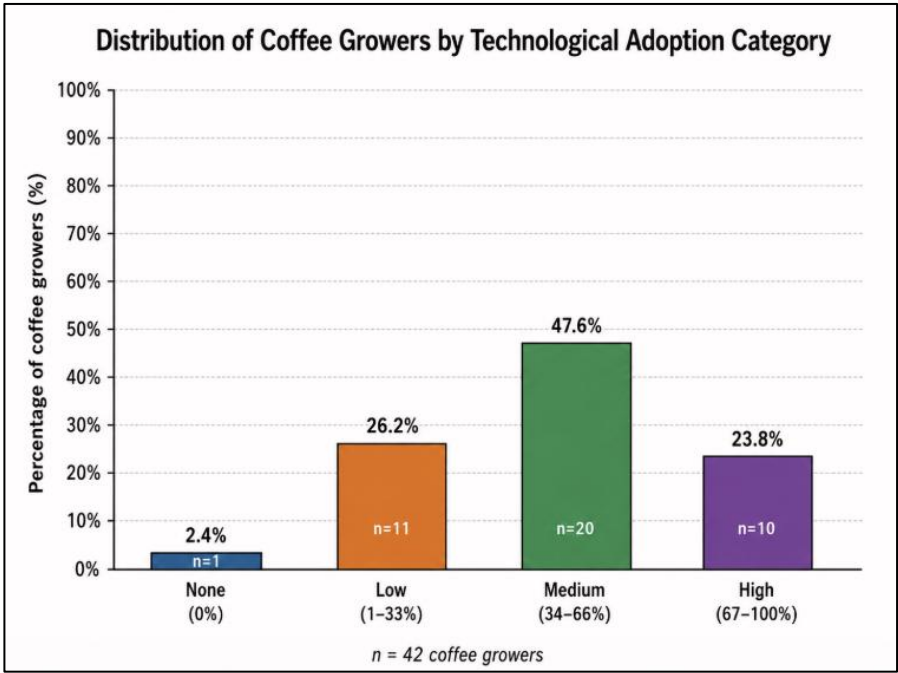
* SMLV: Current Legal Monthly Minimum Wage for 2025: COP 1,423,500 (Decree 1273 of 2024).

Relevant finding: Overall, 52.4% of coffee growers had incomplete primary education, and 83.3% lived on household incomes below one minimum wage. These conditions are typical of family farming in Colombia’s hillside regions and are similar to those reported by Gómez-Castillo and Vargas-Brenes (2024) in Costa Rica, where more than 60% of small-scale coffee growers had incomplete basic education.

Technological Adoption Index (TAI)

The mean TAI for the sample was 48.6% (SD = 18.3), placing the coffee growers in the medium adoption category, corresponding to the implementation of between five and eight practices. The distribution is shown in Figure 1.

Figure 1. Distribution of coffee growers according to technological adoption category.

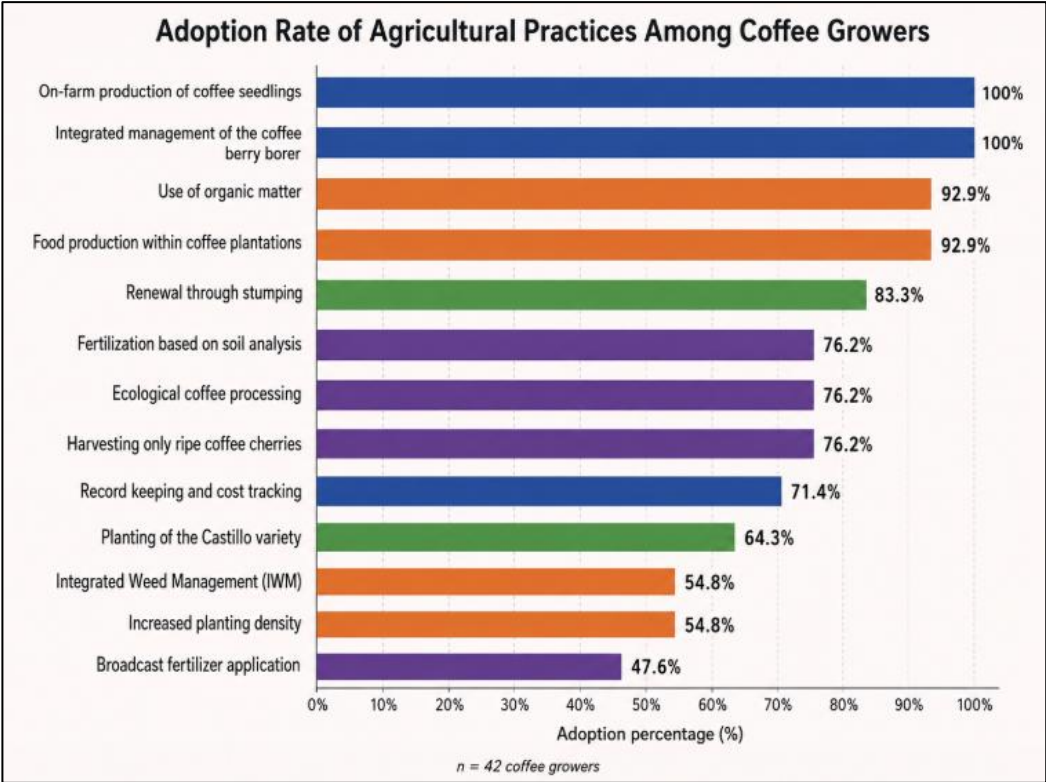


No coffee grower implemented all 12 practices simultaneously. The maximum observed was nine practices, reported by two producers. This finding is consistent with the argument presented by Quirós (2011), as cited in the original document, and supported by Ashadi et al. (2024), who found that adoption in peasant coffee plantations is always selective and depends on the subjective relevance of each practice.

Adoption level by specific practice

Figure 2 shows the percentage of coffee growers implementing each of the 12 practices.

Figure 2. Percentage adoption of the 12 agricultural practices.



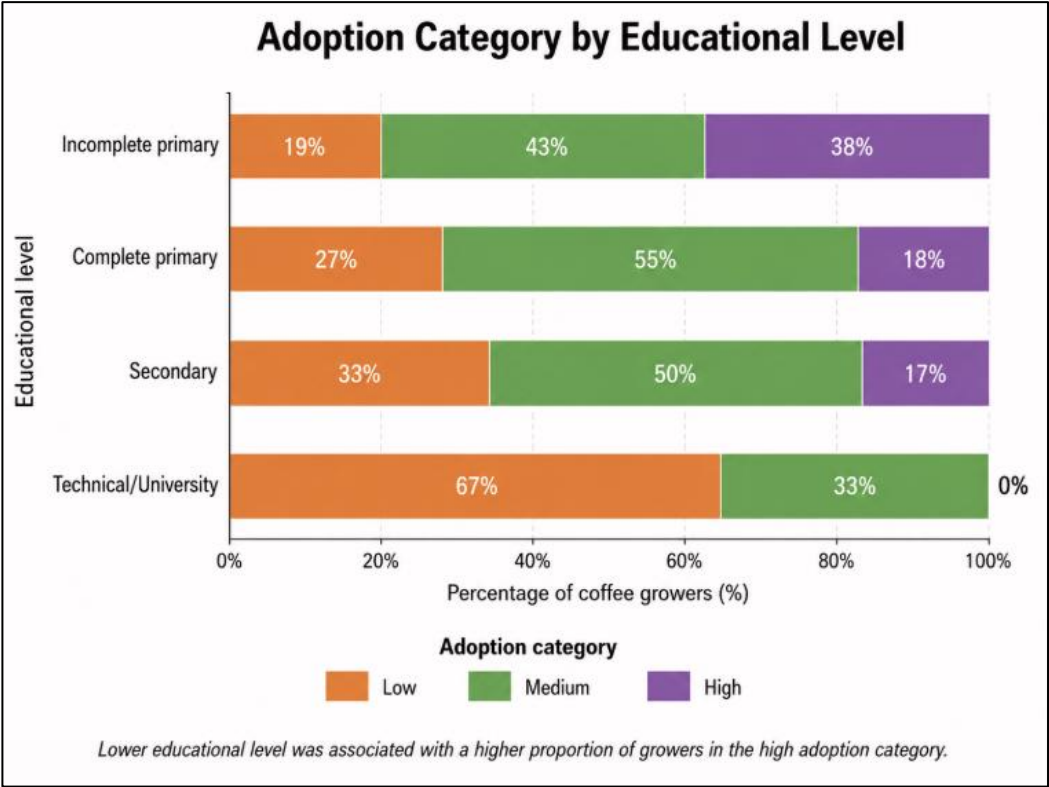
Practices with the highest adoption rates (>90%): seedling production, coffee berry borer management, use of organic matter, and food production. These practices share three characteristics: (1) low additional investment, (2) visible short-term results, and (3) compatibility with traditional practices (Ashadi et al., 2024).

Practices with the lowest adoption rates (<60%): integrated weed management (54.8%), increased planting density (54.8%), and broadcast fertilization (47.6%). The barriers identified were perceived cost, time required, lack of understanding of the concept of “weeds,” and the traditional belief that “throwing fertilizer” is ineffective. This latter finding is consistent with that reported by Carvalho and Toledo (2025) in Brazil, where the adoption of broadcast fertilization is hindered by a cultural preference for localized application.

Determinants of technological adoption

Educational level vs. adoption

Figure 3. Adoption percentage according to educational level.

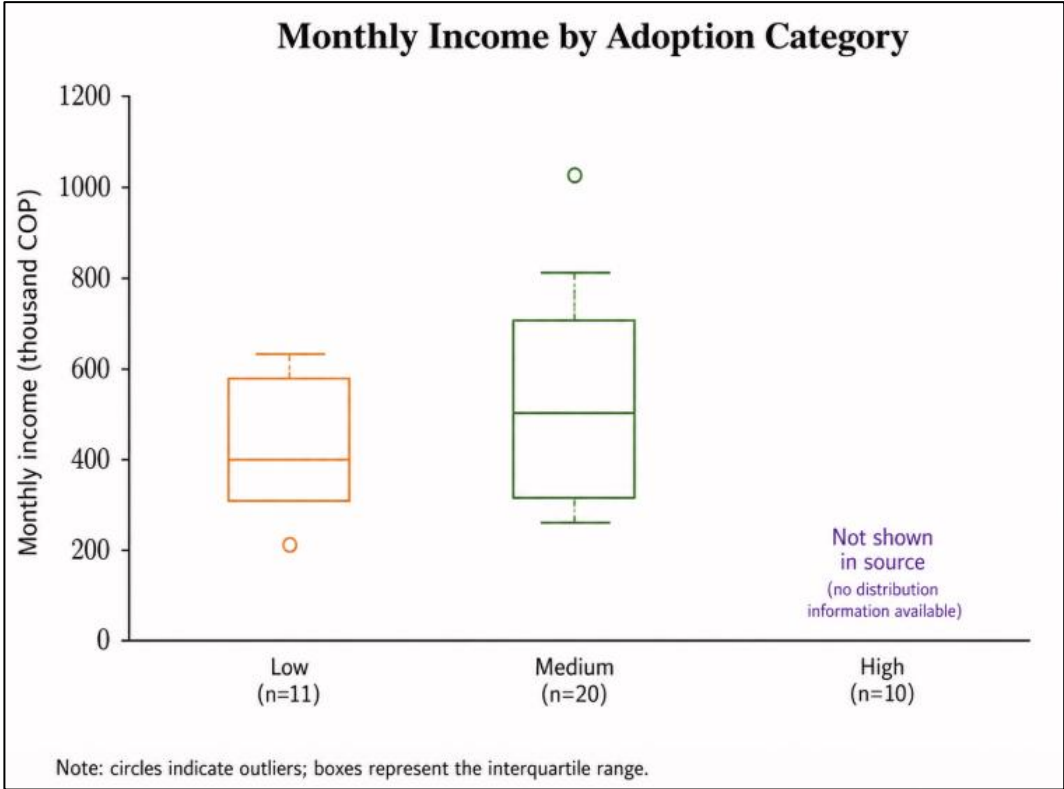


The lower the educational level, the higher the percentage of growers in the “high” adoption category.

Contrary to the initial hypothesis, coffee growers with incomplete primary education showed the highest percentage of high adoption (38%), whereas those with technical or university education did not reach the high adoption category. The chi-square test showed a statistically significant association ($\chi^2 = 8.94$; $df = 4$; $p = 0.039$). This result is consistent with Hossain (1998), as cited in the original document, and with more recent findings by Wambua et al. (2021) in Kenya, where formal education does not always predict adoption when the technology is oriented toward cost reduction and local experience is valued. One possible explanation is that the formal education system in rural areas is not aligned with practical agricultural skills, and that producers with fewer years of schooling rely more heavily on empirical knowledge and the observation of tangible results.

Economic income vs. adoption

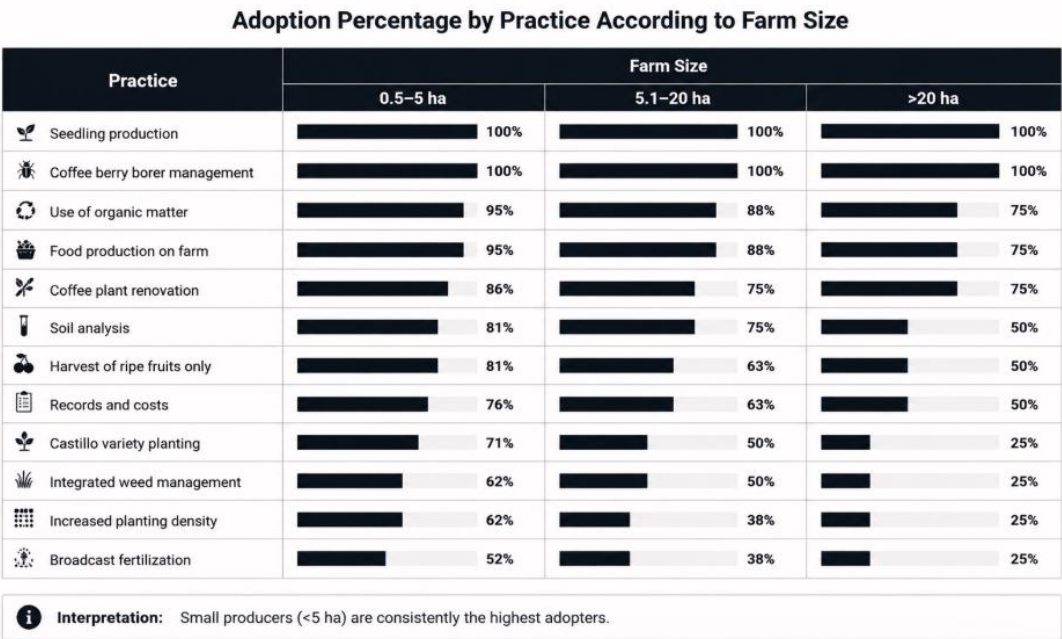
Figure 4. Relationship between monthly income (thousand COP) and adoption category.



Producers in the high adoption category had a mean income of COP 912,000 (SD = 145,000), which was significantly higher ($p < 0.01$; ANOVA $F = 7.84$) than that of producers in the low adoption category (COP 512,000; SD = 198,000). This indicates that technological adoption is not merely a consequence of higher income, but also an investment that can contribute to increasing it. However, the relationship is not linear: medium adopters had intermediate income levels (COP 698,000). The ordinal logistic regression analysis, presented below, confirmed that income was one of the most robust predictors ($\beta = 0.42$; $p < 0.01$).

Farm size vs. adoption

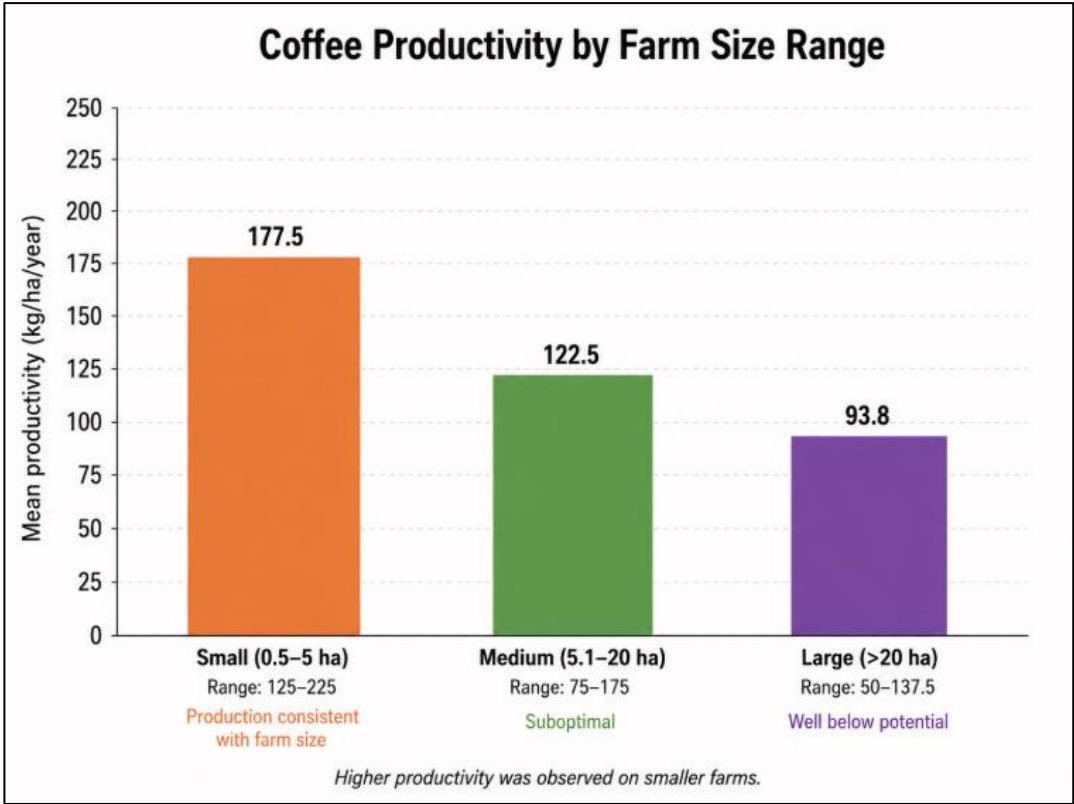
Figure 5. Adoption percentage by practice according to farm size



Coffee growers with smaller farm areas (0.5–5.0 ha) showed the highest adoption percentages for 11 of the 12 practices, with the only exception being planting density. This contradicts the notion that technological adoption requires large production scales. Rather, it suggests that the need to maximize yield per unit area on small farms encourages the search for technologies that reduce costs and increase productivity. Similar findings were reported by Gómez-Castillo and Vargas-Brenes (2024) in Costa Rica, where farms smaller than 3 hectares adopted more integrated management practices than farms larger than 10 hectares.

Productivity vs. farm size

Figure 6. Coffee productivity (kg/ha/year) by farm size range.

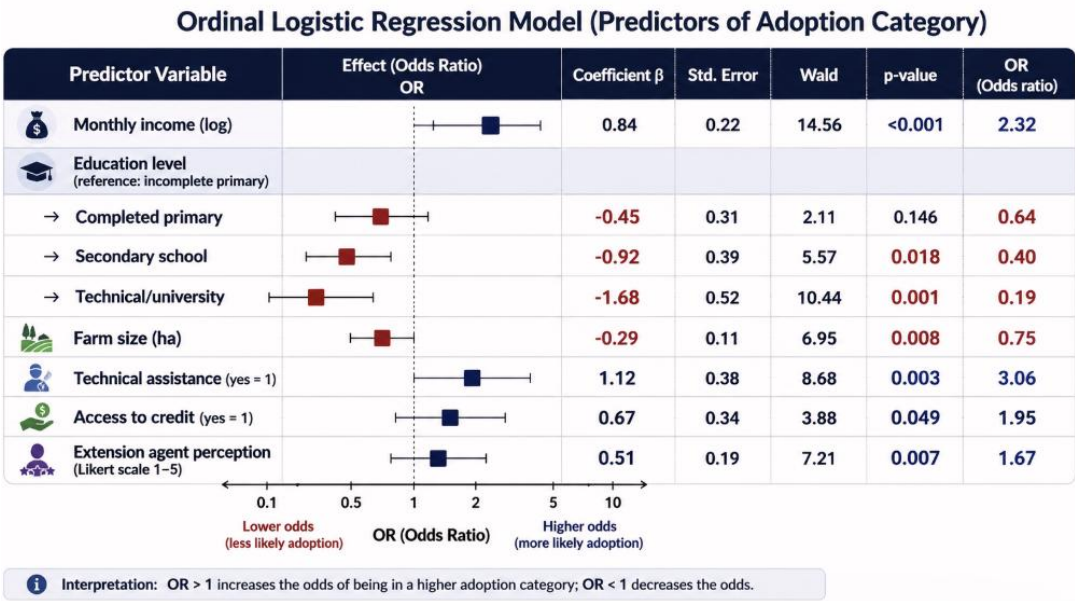


Small farms are more productive per hectare than medium and large farms, which is consistent with the observed inverse relationship between farm size and adoption. This can be explained by a combination of factors, including greater reliance on family labor, more careful application of inputs, and stronger motivation to adopt practices that improve per capita income.

Ordinal logistic regression model (OLR)

To identify the most important predictors of adoption category—low, medium, and high—an ordinal logistic regression model was fitted. Table 4 summarizes the significant coefficient.

Figure 7. Coefficients of the ordinal logistic regression model (dependent variable: adoption category).



Interpretation: The most important predictors were, in descending order of odds ratio magnitude, technical assistance (OR = 3.06), income (OR = 2.32), access to credit (OR = 1.95), and a positive perception of the extension agent (OR = 1.67). In contrast, a higher educational level (secondary or university education) and larger farm size decreased the probability of belonging to a higher adoption category. This model quantitatively confirms the trends observed in the bivariate analyses.

Principal component analysis (PCA) of the 12 practices

The PCA revealed that the 12 practices were grouped into three principal components that explained 71.3% of the total variance (KMO = 0.72; Bartlett’s test: $\chi^2 = 189.4$, df = 66, p < 0.001).

Figure 8. Rotated factor loadings (Varimax method) for the 12 practices

Principal Component Loadings of Agricultural Practices			
Agricultural Practice	Component 1 (Productive efficiency)	Component 2 (Environmental management)	Component 3 (Economic management)
On-farm seedling production	0.82	0.12	0.09
Castillo variety	0.78	0.15	0.10
Renewal through stumping	0.74	0.21	0.18
Increased planting density	0.69	0.08	0.22
Integrated coffee berry borer management	0.23	0.79	0.11
Integrated weed management	0.11	0.76	0.14
Organic matter	0.28	0.71	0.19
Ecological coffee processing	0.15	0.68	0.24
Fertilization based on soil analysis	0.24	0.18	0.81
Broadcast fertilization	0.09	0.21	0.78
Harvesting only ripe coffee cherries	0.31	0.19	0.70
Record keeping and cost analysis	0.18	0.24	0.68

Higher loadings indicate stronger association with the component.

Component 1, productive efficiency, brings together practices aimed at increasing the physical productivity of the crop, such as improved varieties, renewal, and planting density. Component 2, environmental management, integrates practices with a positive impact on ecological sustainability, including biological control, ground cover management, reduction of chemical inputs, and water savings. Component 3, economic management, groups practices that improve input-use efficiency and business decision-making.

This finding is relevant because it shows that coffee growers do not adopt technologies in isolation; rather, they tend to adopt packages of practices that are consistent with a dominant productive logic. However, only 23.8% of producers reached the high adoption category, and, overall, the adoption of practices within the environmental component, such as weed management and ecological coffee processing, was lower, revealing tensions with sustainability.

4. Discussion

The education paradox: less schooling, greater adoption

One of the most contradictory findings was the inverse relationship between formal educational level and degree of adoption. Far from being an anomaly, this result has been documented in other family farming contexts. Wambua et al. (2021) found in Kenya that small-scale coffee growers with

incomplete primary education more frequently adopted improved varieties and integrated pest management than those with secondary education. They attributed this pattern to the fact that the former have fewer alternative income options and, therefore, a greater willingness to test innovations that promise rapid returns. In a similar study in Ethiopia, Asfaw et al. (2021) noted that formal education may sometimes generate a “scrutiny effect”: more educated producers tend to question technical recommendations and demand more rigorous evidence, which may delay adoption.

In the Colombian case, it is plausible that the rural education system has not developed practical competencies for agricultural innovation, and that coffee growers with incomplete primary education rely more heavily on horizontal socialization, that is, learning from other producers, than on extension agents or technical manuals. This finding has important policy implications: it should not be assumed that increasing schooling alone will lead to greater adoption; rather, educational content must be aligned with the needs of the agricultural sector.

The role of income and credit: adoption is costly, but non-adoption is costlier

The statistical models showed that income and access to credit are significant predictors of adoption. However, the relationship is not simply “higher income–greater adoption”; rather, adoption itself may contribute to increasing income, suggesting possible reverse or bidirectional causality. Carvalho and Toledo (2025), using a structural equation model in Brazil, demonstrated that the adoption of sustainable practices, such as ecological coffee processing and weed management, generates economic returns within a period of two to three years, thereby reinforcing a virtuous cycle.

A concerning result is that only 28.6% of producers had access to agricultural credit. By contrast, Gómez-Castillo and Vargas-Brenes (2024) reported that, in Costa Rica, 65% of small-scale coffee growers have access to specific credit lines for technological reconversion, which facilitates the adoption of practices with high initial costs, such as ecological coffee processing or increased planting densities. The low coverage of credit in Piendamó therefore constitutes a structural barrier that perpetuates low productivity.

Farm size and productive efficiency: a lesson for agrarian policy

The higher adoption and productivity observed on small farms, those smaller than 5 ha, challenges the paradigm that agricultural modernization requires land concentration. On the contrary, it supports the thesis of efficient family farming (Altieri & Nicholls, 2020), according to which small units under intensive family labor management can achieve higher yields per hectare than large extensive farms. In a recent analysis of coffee farming in Mexico, Briones-Ruíz and Juárez-Sánchez (2021) found that the density of social ties and trust among neighbors, which are more common in small-holder communities, facilitate the diffusion of innovations. In San Pedro, small producers not only adopt more practices, but also share seeds, seedlings, and knowledge, creating a local learning network that institutional extension agents are unable to replicate.

The extension gap: from facilitator to administrator

The regression model showed that technical assistance was the strongest predictor of high adoption (OR = 3.06). However, 23.8% of producers reported not receiving assistance or not knowing of any institution that provides it. In addition, complementary interviews, not quantified in this study, revealed that extension agents from the Coffee Growers Committee have seen their administrative duties multiply, including credit management, program supervision, and reporting, thereby reducing their time in the field. This phenomenon has been widely documented in Latin America: extension agents who become “project managers” lose the capacity to build knowledge dialogue and trust with farmers (Ortiz & Perafán, 2020). By contrast, rural extension programs that adopt participatory and horizontal learning approaches, such as Farmer Field Schools, have shown adoption rates up to 40% higher than traditional vertical technology transfer models (Davis et al., 2022).

In San Pedro, field verification showed that producers who perceive the extension agent as an ally, with Likert scores ≥ 4 , are 1.67 times more likely to be in the high adoption category. This suggests that social ties and trust are as important as the technical content of the recommendations.

Tensions between technological adoption and environmental sustainability	537
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The principal component analysis revealed that the practices with the	540
lowest adoption rates corresponded to Component 2, environmental man-	541
agement: integrated weed management (54.8%) and ecological coffee pro-	542
cessing (76.2%, although relatively high, still not universal). In addition,	543
direct observation showed that many producers continue to use burning	544
and hoeing for weed control, practices that erode hillside soils and reduce	545
biodiversity.	546
	547
This tension is not exclusive to Piendamó. Harvey et al. (2021) pointed out	548
that, throughout Latin America, the transformation of coffee landscapes	549
toward more intensive systems has led to forest loss, declining ecosystem	550
services, and soil degradation. The adoption of “green” practices often re-	551
quires initial investment, changes in cultural routines, and a long-term re-	552
turn horizon, whereas poor coffee growers tend to heavily discount the	553
future, preferring immediate benefits. Closing this gap therefore requires	554
more than technology transfer; it also demands economic incentives, such	555
as payments for ecosystem services and differentiated prices for sustaina-	556
ble coffee, as well as continuous support (Carvalho & Toledo, 2025).	557
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Recommendations for rural extension and sustainable development de-	559
rived from the study	560
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Differentiated strategies should be designed according to farm size and	562
educational level. Since small producers are the most receptive, they	563
should be the priority focus. For producers with higher levels of formal	564
education, more robust technical and economic arguments are required,	565
along with locally validated evidence.	566
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Specific soft credit lines should be created for the adoption of environ-	568
mental practices, such as ecological coffee processing, integrated weed	569
management, and agroforestry systems, with grace periods and linked	570
technical assistance. The low coverage of credit identified in this study	571
could be mitigated through partnerships between the Coffee Growers	572
Committee and rural financial institutions.	573
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Food production within coffee plantations should be strengthened as a dual strategy for food security and income diversification. This practice shows high adoption, at 92.9%, and generates tangible benefits; it could be expanded by promoting local markets for plantain, maize, and fruit crops.

A technological adoption monitoring system should be implemented, including environmental sustainability indicators. The TAI developed in this study could be adapted as a diagnostic tool by extension agents, allowing the identification of gaps by component: productive, environmental, and economic.

Direct economic incentives, such as payments for ecosystem services, should be explored for practices such as integrated weed management and ecological coffee processing. Adoption of these practices remains below 80%, despite their critical impact on sustainability. Programs such as BanCO2 in Colombia and Payments for Ecosystem Services in Coffee in Costa Rica offer useful lessons learned.

The relationship between formal education and technology transfer should be reconsidered. Practical modules on sustainable coffee farming should be incorporated into rural primary and secondary school curricula, and internships for young people should be established on demonstration farms managed by high adopters.

5. Conclusions

Technological adoption is selective and pragmatic, and lower levels of formal education do not constitute an obstacle but rather a factor associated with higher adoption: 38% of coffee growers with incomplete primary education were classified in the high adoption category, compared with 0% among those with higher education.

This challenges the assumption that increasing schooling alone accelerates innovation. What is required is a rural extension approach based on experiential learning and dialogue among knowledge systems, rather than on the vertical transfer of knowledge.

Technical assistance (OR = 3.06) and credit access (OR = 1.95) are the strongest institutional predictors of adoption, but their coverage remains insufficient, with only 28.6% of producers having access to credit. Without these two enabling factors, environmentally important practices, such as ecological coffee processing and weed management, will remain marginal.

Strengthening participatory extension and expanding soft credit lines is therefore more effective than any isolated technology transfer effort.

Small farms, under 5 ha, adopt more practices, 11 out of 12, and are more productive than large farms, with 14.2 vs. 7.5 qq/ha, challenging the paradigm that modernization requires land concentration. However, environmental sustainability practices, corresponding to Component 2 of the PCA, show the lowest adoption rates, below 76%. Therefore, policy should promote smallholder farming while creating specific incentives, such as payments for ecosystem services, to decouple productive efficiency from ecological degradation.

The extension agent–coffee grower gap is both institutional and relational in nature: extension agents, overwhelmed by administrative duties, have reduced their fieldwork and dialogue with farmers, thereby eroding trust. Producers who perceive the extension agent as a close ally are 1.67 times more likely to reach high adoption. It is therefore necessary to redefine the role of the extension agent as a facilitator of horizontal learning processes, such as Farmer Field Schools, rather than as a bureaucratic manager.

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