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Article

Sustainability of coffee farms: Case study of the cooperativa agraria Cafetalera La Prosperidad de Chirinos

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Abstract: Ignorance of the sustainability of coffee systems compromises the continuity of productive activities by weakening their economic viability, environmental integrity and social cohesion over time, which is why it is essential to carry out diagnoses. This study aimed to assess the sustainability level of coffee farms associated with the Cooperativa Agraria Cafetalera La Prosperidad de Chirinos. From January to March 2024, data were collected from 60 farms out of a population of 788. The analysis was based on nine criteria: six environmental (soil quality, crop health, solid waste and effluent management, integrated pest and disease management, ecological knowledge, and agricultural system), two economic (agricultural economy and food sovereignty), and one social (social aspects). To identify groups of farmers with homogeneous characteristics, a cluster analysis was performed and the level of sustainability of each group was determined by calculating overall averages, represented through Amoeba charts. Results identified two farm types farms in group 1 showed less sustainability than group 2, mainly due to unfavorable conditions related to soil quality. Consequently, it is recommended to to implement cover crops, live barriers, infiltration ditches, contour planting, and productive diversification for food security are recommended. This study provides a scientific diagnosis of sustainability levels on coffee farms and offers practical options for improving sustainability.

Keywords: sustainable development; Coffea arabica; sustainability assessment sustainability indicators; food security; cluster analysis Peru

1. Introduction

Sustainability in agri-food systems has become increasingly important in light of the challenges posed by climate change, soil degradation, and pressure on natural resources. In this context, coffee—a strategic crop in countries in the global south—faces the challenge of maintaining its productivity without compromising environmental health or social equity. Sustainable coffee production seeks to reduce deforestation, improve efficiency in the use of inputs, and strengthen rural livelihoods, especially in areas of high biodiversity such as the Peruvian Andes [1,2].

Coffee is mainly produced by smallholder farmers [3,4], living in approximately 50 producing countries in the southern hemisphere [5], facilitating the livelihoods of 25 million farmers globally [6,7] in addition to providing work for 125 million people in Latin America, Africa and Asia [8]. With coffee being the world's second most consumed beverage, and global demand steadily increasing, the urgency to ensure sustainability across production systems has never been greater [2,9]. However, most studies on coffee sustainability have focused on Central America, Africa, and Asia, leaving the production realities of Peruvian cooperatives, such as La Prosperidad de Chirinos, underrepresented.

In Peru, coffee is grown in the inter-Andean valleys and on the eastern slopes of the Andes, and is the main crop in terms of surface area and agricultural exports. More than 223,000 families depend on this activity, with 75% of production above 1000 meters above sea level, concentrated in San Martín, Junín, Cajamarca, and Amazonas [10], reflecting a strong national interest in coffee consumption and production [11]. Despite their strategic importance, there are gaps in the characterization of the sustainability of Peruvian coffee farms, especially with regard to environmental efficiency, waste management, soil conservation, and the adoption of agroecological practices [12,13].

From a scientific point of view, one of the main challenges is to develop accessible methodologies that allow for a comprehensive assessment of farm sustainability, simultaneously considering environmental, economic, and social dimensions. Previous studies have addressed isolated indicators or qualitative approaches, without offering comparative tools to facilitate technical and policy decision-making. In addition, there remains the difficulty of classifying farms according to their level of sustainability, which limits the targeting of interventions and the design of differentiated strategies [11].

The analysis of sustainability in farms contributes to propose strategies and to make decisions on the productive processes developed in each farm according to its characteristics [14]. Sustainability assessment can be developed through practical and simple methodologies + for example, the use of indicators that allow determining the current state of a given agricultural system [15]. When analyzing each indicator, sustainability can be determined through "Amoeb" type diagrams that the closer to the diameter of the circle (the optimum is a value of 10) the more sustainable they are [14]. Although it is true that the evaluation of sustainability is based on the analysis of economic, environmental and social aspects, it is also necessary to classify each farm according to its characteristics of similarity and differences, which can lead to a more adequate analysis of its level of sustainability [14,15]. In this context, the general objective of the research was to determine the level of sustainability of the coffee farms belonging to the Cooperativa Agraria Cafetalera La Prosperidad de Chirinos.

2. Materials and methods

2.1. Location of the study

The research was conducted from January to March 2024, in the districts of

Chirinos, La Coipa and Huarango, province of San Ignacio, department of Cajamarca (**Figure 1**), with a territorial extension of 352.00 km^2, 417.00 km^2, and 906.00 km^2 respectively. It has a mean annual maximum temperature of 22.4 °C and a minimum of 15.3 °C, annual precipitation of 1324 mm and relative humidity of 86%, data taken from the Chirinos meteorological station (5°18'30.59"S. Lat., 78°53'51.32"W. Long.).

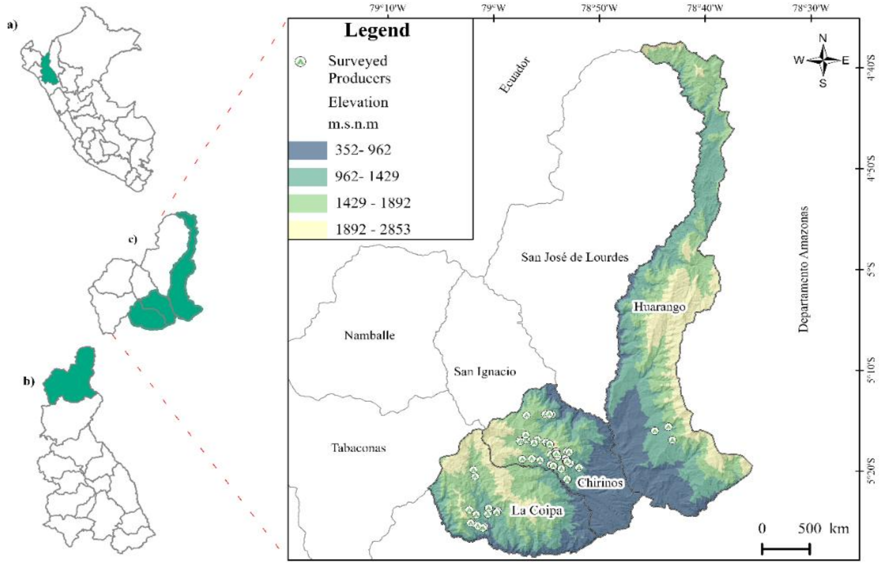


Figure 1. Distribution map of the coffee farms evaluated.

2.2. Sampling

The sample was determined based on the total population of members of the Cooperativa Agraria Cafetalera La Prosperidad de Chirinos, which was 788 for January 2024. The sample size was estimated using the formula for finite populations; using a confidence level of 95%, probability of success of 80%, error of 20% and estimation error of 10% [14]. The probability of success was based on preliminary diagnostics that indicated that between 75% and 85% of producers were adopting at least half of the sustainable practices evaluated. In addition, this value allows us to maintain an adequate sample size and reasonable precision considering the logistical and accessibility limitations of the study. The application of this formula made it possible to obtain a sample of 60 coffee farms and the sampling was random.

$$n = \frac{N \times Z_{\alpha}^{2} \times p \times q}{e^{2} \times (N-1) + N \times Z_{\alpha}^{2} \times p \times q} \quad (1)$$

where, n = sample size, N = population size, Z = 95% confidence level, e = 10% estimation error, p = 80% probability of success, q = 20% probability of error (1–p).

2.3. Data collection and indicators

A survey and field data collection form was applied to the 60 partners, a methodology was adapted to infer soil quality, crop health, solid waste and effluent management, integrated pest and disease management, ecological knowledge, agricultural system, agricultural economy, food sovereignty and social aspects through different indicators that were constructed from previously published works by de García GPTJ et al [14] and Altieri et al. [15]. The methodology indicated by Reis et al.

[16] was applied, focusing on the perception of indicators shown at a level of their state, assigning qualitative values according to the observed condition, thus, a condition between less desired to moderate received values from 1 to 5; between moderate and desired received values from 5 to 10; in summary, the value 1 indicates the worst or least desired condition, while 10 represents the ideal or most desired condition. To mitigate potential biases in perception-based metrics, surveyors were trained using standardized semantic guides and anchors.

Thirty-four indicators were analyzed and divided into nine criteria, six of which were environmental, two economic and one social. The details of each indicator are shown in **Table 1**.

Table 1. Environmental, economic and social indicators for sustainability analysis of the coffee systems of the PCooperativa Agraria Cafetalera La Prosperidad de Chirinos.

Dimension	Criteria	Indicator	Feature
Environmental	Soil quality	Depth of the arable layer of soil	Exposed soil with rocky outlook (1), thin soil layer (5), top soil >50 cm (10)
		Color of organic matter	Pale, absence of organic matter (1), light brown, some presence of organic matter (5), dark brown, abundant organic matter (10)
		Ground cover	No cover, 100% exposed (1), soil with less than 50% covered (5), more than 50% covered (10)
		Presence of landslides, ruts, gullies and/or loss of cover.	Presence of gullies, landslides, absence of vegetation cover and terraces (1), presence of small ruts and compacted areas without vegetation (5), no presence of gullies, ruts or deep channels caused by rain, no landslides, good vegetation cover, terraces (10)
		Slope of the farm	Greater than 30% (1), between 30 and 15% (5), less than 15% (10)
		Soil conservation technology	( ) Cover crops ( ) Live barriers ( ) Dead barriers ( ) Contour lines ( ) High coffee density (>7500 plants/ha) ( ) Infiltration ditches ( ) Agroforestry systems Other: .... Less than 2 practices (1), between 2 and 4 practices (5), more than 5 practices (10).
	Crop health	Appearance	Chloritic (1), light green color with some loss of pigment (5), dark green color, no deficiency symptoms (10)
		Presence of pests and diseases	Greater than 15% (1), between 15 and 5% (5), less than 5% (10)
		Weed control	Control with herbicides and/or manual control with lampa (1), Manual control with machete or scythe (5), Decrease in planting distances between plants and furrows, using dead cover (10).
		Presence of trees on the farm	No trees (1), <50 trees per hectare (5), >50 trees per hectare (10)
Environmental	Solid waste and effluent management	Management of pruning and litter residues	Waste is thrown into the river, stream or other water source or burned (1), waste is thrown into a dumpster on the farm (5), waste is incorporated into the soil or left on the soil surface (10).
Environmental Economic	Solid waste and effluent management Integrated pest and disease management	Domestic solid waste management	Open dumping, burning, improper burial (1), separation at source (5), separation at source, recycling, composting (10)
		Harvest residue management (coffee pulp)	No treatment (1), poor composting process (5), good composting process (permanent turning, humidity control, incorporation of efficient microorganisms) or other type of utilization (10).
		Honey water management	The honey water is disposed of without any prior treatment (1), the honey water is disposed of in a honey water well with no evidence of honey water management (5), the honey water is disposed of in a honey water well or other type of treatment and there is evidence of honey water management (10).

Table 1. (*Continued*).

Dimension	Criteria	Indicator	Feature
	Integrated pest and disease management Ecological knowledge	Cultural control of pests and diseases (shade regulation, pruning, timely harvesting, weed control).	Not effective (1), moderately effective (5), effective and applied to control Hypothenemus hampei (borer), Hemileia vastratrix (rust), etc. (10).
		Costs of integrated management	Is expensive, inaccessible (1), Is moderately expensive, accessible (5), Not expensive, accessible (10)
		Is aware of local, national and global environmental issues.	No environmental awareness at all (1), has a biased view of environmental awareness (5), has a holistic view of environmental awareness (10), has a partial view of environmental awareness (5), has a holistic view of environmental awareness (10).
	Agricultural system	On-farm water supply	Rainwater reservoirs (1), harnesses rivers or streams (5), has a water piping system (10)
	Agricultural system Agricultural economy	Sanitary facilities on the farm	No latrine (1), has latrine, cesspool (5), has drainage system, cesspool (10)
		Forest areas	No forest reserves (1), has a forest reserve without timber species (5), has a forest reserve with timber species and wild animals (10)
		Reforestation	No reforestation (1), little reforestation (5), regular reforestation in crops and free areas (10).
		Crop diversity	Single crop (1), two crops in the same lot (5), more than three crops in the same lot (10)
Economic	Agricultural economy	Calidad de la vivienda en la finca	Very humble, material of the area (1), regular, some comfort, with transformed materials (5), comfortable, with finishing materials (10).
		Tools and equipment	Basic tools, machete, axe, lampa (1), few non-basic tools (5), uses many tools per activity (10).
		Vehicle	Does not have (1), has non-motorized (5), has motorized (10)
		Origin of reported income	Reported income is mainly from business or salaried work (1), reported income is due to additional business or salaried work and to a lesser extent from agricultural activities (5), reported income is due to agricultural activities and to a lesser extent from additional business or salaried work (10).
		Other income	Does not have (1), performs tasks temporarily away from the farm (5), works simultaneously, has permanent outside work (10)
		Personnel for farm work	Does not hire (1), hires temporarily (5), hires permanently (10).
Economic	Agricultural economy	On-farm production costs (FPC)	FPC have higher percentage in: agrochemical fertilizers, purchase of fuels or rental and/or purchase of machinery (1), CPF have higher percentage in: purchase of seeds, rental and/or purchase of tools or irrigation (aqueduct service) (5), farms in which production costs have higher percentage in: payment of labor (10).
Economic Social	Agricultural economy Food sovereignty	Bank credit	No access to credit (1), has credit for personal expenses (5), has bank credit for farm investment (10).
		Source of food inputs	Farmers who buy everything from the winery or from their neighbors (1), farmers who consume what they produce and buy from the wineries (5), farmers who consume what they produce, buy from their neighbors and to a lesser extent from the wineries (10).
	Social aspects	Distance from the nearest medical center	More than 5 km (1), between 5 and 2 km (5), less than 2 km (10)
Social	Social aspects	Educational level of children	Not studying, or only in primary school (1), studying in secondary school (5), studying in high school or university (10)
		Services available at the farm	No electricity and no nearby water source (1), with electricity and nearby water source (5), with access to sewage and telephone (10)

Source: adapted from Altieri [15], Cerón WL, Escobar YC, Díaz ÁJÁ [17] and Leiva [18].

2.4. Farm classification and sustainability assessment

From the 34 indicators, coffee systems were associated according to their similarities through a hierarchical cluster analysis. Ward's method was used to determine the minimum differences of farmers within groups and maximum differences between groups. The analysis showed two types of coffee systems. Then, a description of the types of systems defined was made, highlighting the differentiating characteristics between groups; finally, Ameba graphs were made to analyze the status of each indicator and its effect on the sustainability of each group of coffee farms defined. The value of the evaluation criterion is the result of the average of each indicator that is part of each criterion, a value of five was considered as the sustainability threshold [14] because it is the midpoint of an ideal condition. Based on the analysis of the level of sustainability, proposals were developed for each type of farm.

2.5. Statistical analysis

The coffee systems were typified by means of a cluster analysis following Ward's method and Jaccard's distance as a grouping technique, whose variables were previously standardized for processing; this analysis was developed in the RStudio programming environment. Qualitative variables were analyzed with contingency tables and Chi-square test, while quantitative variables were evaluated with the *T*-test ($p < 0.05$) after verifying the normality of the data using the Shapiro-Wilk test performed in StatGraphics Centurion XVI software (StatPoint Technologies Inc., Warrenton, VA, USA).

3. Results

In general, less than 5% of the coffee growers evaluated have no education at all, more than 50% have primary education, 20% have secondary education and 18% have higher education. The hierarchical cluster analysis identified two defined types of coffee farms at the height of 15. The first group, assigned as group 1, grouped 35% of the farms while the second, group 2, grouped the remaining 65%. Group 1 was characterized by greater internal homogeneity and smaller average distance between members, while group 2 was characterized by greater internal dispersion (**Figure 2**).

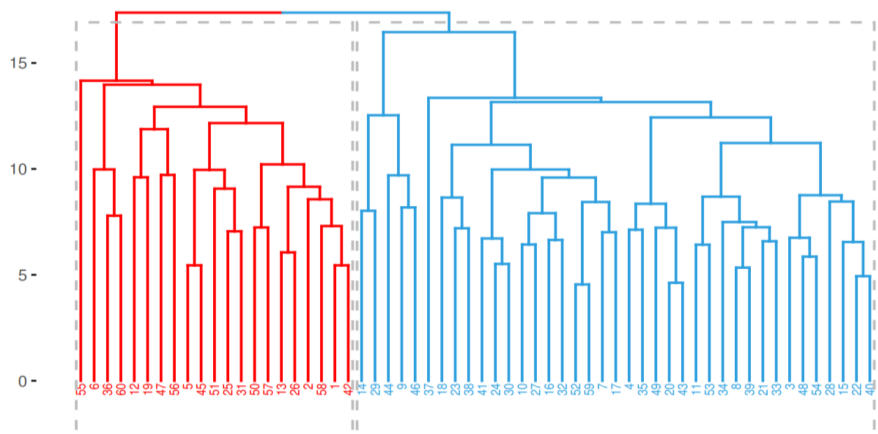


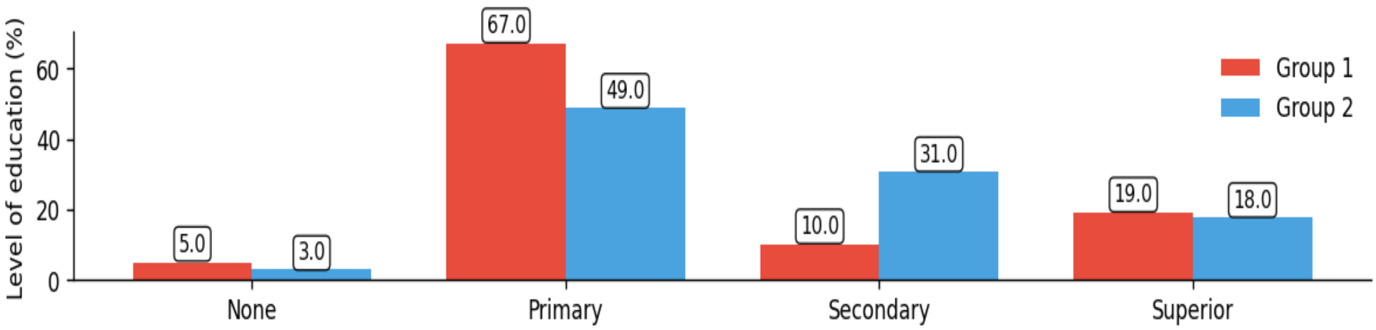
Figure 2. Formation of groups of coffee farms according to Ward's methodology.

The characteristics of the producers of the Cooperativa Agraria Cafetalera La Prosperidad de Chirinos according to the type of coffee system show that for both groups the average age of coffee farmers is above 50 years, there is a small percentage (3%–5%) of farmers with no education, about 50% have primary education and at least 18% have higher education. Regarding coffee production, the results of group 2 were 16% higher than those of group 1. On average, group 2 produced 27.7 qq/ha, representing 8% more than group 1; total income from coffee sales does not differ between groups (40 453 ± 24 504 vs. 35 230 ± 23 048). Land use shows the clearest contrasts. Group 2 manages a significantly larger total land area (5.40 ± 3.20 vs. 3.00 ± 1.40 ha; $p < 0.001$) and allocates more area to wintering (0.70 ± 1.00 vs. 0.20 ± 0.40 ha; p = 0.004) and stubble (0.50 ± 1.00 vs. 0.10 ± 0.20 ha; $p = 0.01$). Age, coffee tree quintals, total income from coffee sales, productivity, coffee tree area, and forest area did not show significant differences ($p > 0.05$) (**Figure 3a, b**).

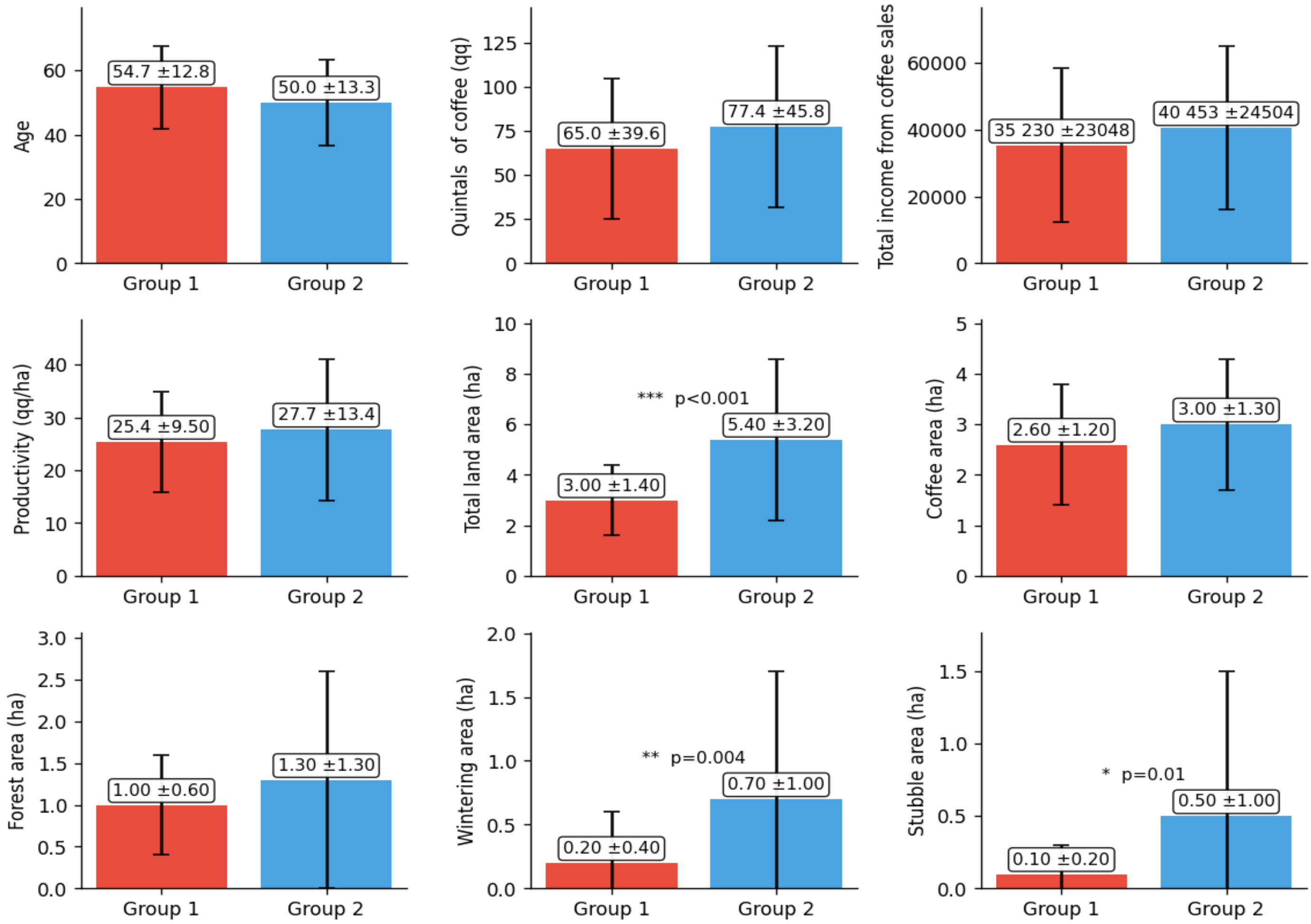
The analysis of averages by criterion group 1 and group 2 exceeded the average of the sustainability threshold, with the sole exception of "Soil quality" in Group 1 (4.8 ± 2.2), which was below the established level. The highest scores in the two groupings corresponded to "Solid waste and effluent management" (G1: 7.3 ± 2.1; G2: 8.3 ± 1.6) and "Integrated pest and disease management" (G1: 7.9 ± 2.6; G2: 8.7 ± 1.3) (**Table 2**, **Figure 4a, b**).

When comparing between groups, Group 2 showed significant advantages in Soil quality (5.5 ± 2.4 vs. 4.8 ± 2.2; $p = 0.030$), Waste and effluent management (8.3 ± 1.6 vs. 7.3 ± 2.1; $p = 0.002$), Integrated pest and disease management (8.7 ± 1.3 vs. 7.9 ± 2.6; $p = 0.030$), Production system (7.8 ± 2.4 vs. 5.8 ± 3.2; $p = 0.000001$) and Farm economics (6.7 ± 2.3 vs. 5.8 ± 2.8; $p = 0.0002$). No differences were observed in Crop health (6.6 ± 2.5 vs. 6.5 ± 2.7; $p = 0.686$) and Food sovereignty (5.3 ± 2.4 vs. 5.9 ± 3.3; $p = 0.438$). Ecological knowledge showed a trend in favor of Group 2 ($p = 0.085$), while in social aspects Group 1 was superior (6.7 ± 3.0 vs. 5.6 ± 3.1; $p = 0.044$) (**Table 2**, **Figure 4a, b**).

The overall sustainability index, calculated as the average of the nine criteria, exceeded the threshold in both groups, with averages of 6.4 ± 2.7 (Group 1) and 7.0 ± 2.3 (Group 2), confirming acceptable overall performance and, in relative terms, better overall performance of Group 2 in most of the domains evaluated (**Table 2**, **Figure 5**).



(a)



(b)

Figure 3. Characteristics of the producer of the Cooperativa Agraria Cafetalera La Prosperidad de Chirinos according to the type of coffee system. Level of education of producers **(a)**; socioeconomic and productive characteristics of producers **(b)**. Bars show mean ± standard deviation. Significance between groups (*p*-value) is indicated by asterisks. Note: $p < 0.05$ = *, $p < 0.01$ = **, $p < 0.001$ = ***.

Table 2. Average according to criteria for the classification of sustainability indicators according to the type of coffee system of the Cooperativa Agraria Cafetalera La Prosperidad de Chirinos.

Criterion	Group 1	Group 2	Significance
Soil quality	4.8 ± 2.2	5.5 ± 2.4	0.030
Crop health	6.5 ± 2.7	6.6 ± 2.5	0.686
Solid waste and effluent management	7.3 ± 2.1	8.3 ± 1.6	0.002
Integrated pest and disease management	7.9 ± 2.6	8.7 ± 1.3	0.030
Ecological knowledge	6.9 ± 2.5	8.1 ± 2.5	0.085
Farming system	5.8 ± 3.2	7.8 ± 2.4	0.000001
Agricultural economics	5.8 ± 2.8	6.7 ± 2.3	0.0002
Food sovereignty	5.9 ± 3.3	5.3 ± 2.4	0.438
Social aspects	6.7 ± 3	5.6 ± 3.1	0.044
General sustainability index	6.4 ± 2.7	7.0 ± 2.3	

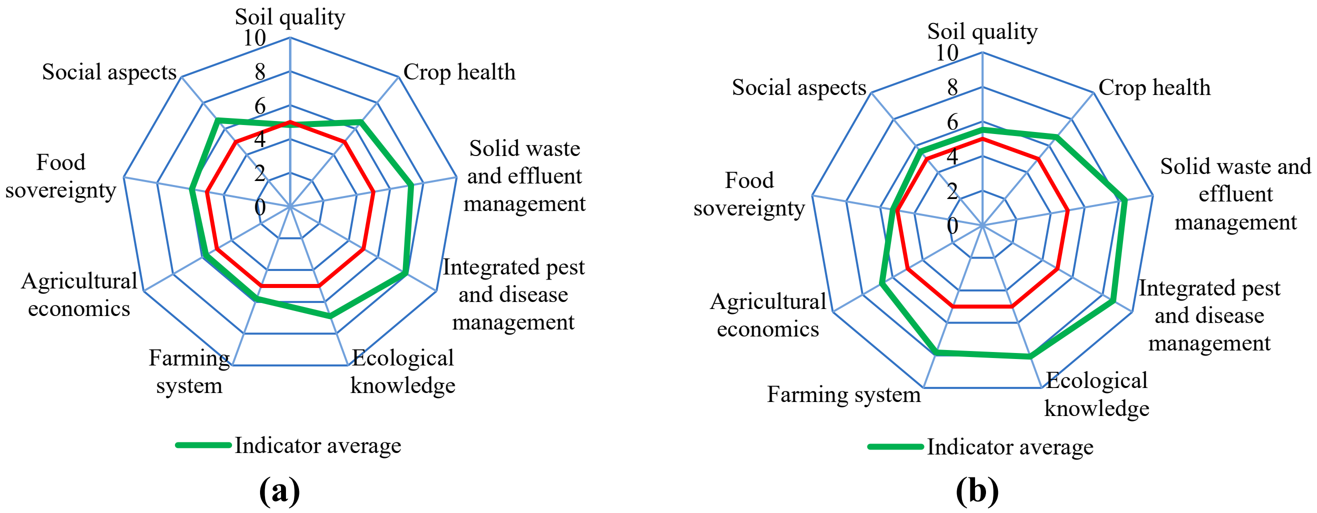


Figure 4. Ameba graphs for sustainability analysis according to the nine evaluation criteria in two types of coffee farms. group 1 **(a)**; group 2 **(b)**, of the farmers of the Cooperativa Agraria Cafetalera La Prosperidad de Chirinos.

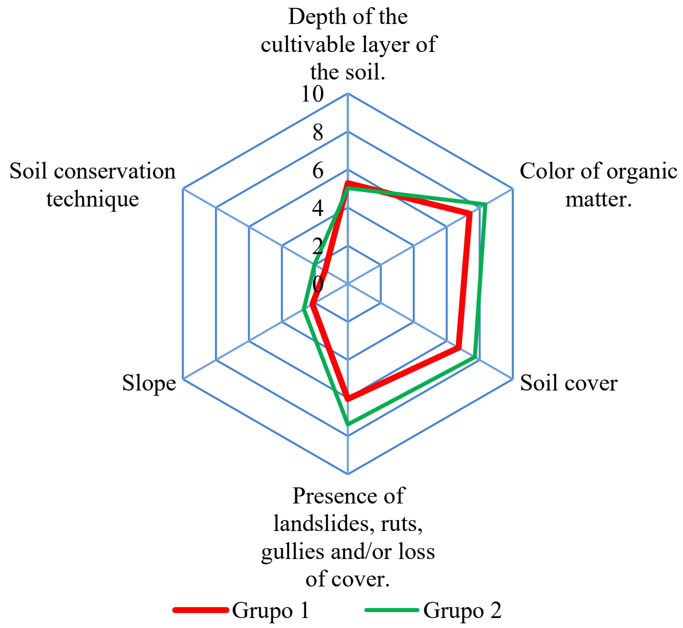


Figure 5. Ameba graph for analysis of critical sustainability indicators in two types of coffee farms of farmers of the Cooperativa Agraria Cafetalera La Prosperidad de Chirinos.

4. Discussion

The diagnosis of the sustainability of coffee systems is key to defining actions that ensure productive continuity without compromising economic viability, environmental integrity or social cohesion over time [19]. This study evaluated the level of sustainability of coffee farms of the Cooperativa Agraria Cafetalera La Prosperidad de Chirinos with a practical and reproducible evaluation methodology. The study population was identifying groups with homogeneous characteristics and determining their respective level of sustainability.

The typification of farms through multivariate cluster analysis is a useful strategy for grouping individuals with similar characteristics within the group and more distant between groups [14,20,21]. The hierarchical cluster analysis identified two defined types of coffee farms. this classification makes it possible to describe the main characteristics of coffee growers and farms in each defined group. Most indicators did not show significant differences between groups. The average age of coffee growers was 50 years old. (regardless of the group they are in), this age highlights two problems; the first is related to generational replacement, there are fewer young people who want to engage in coffee growing and choose to study and/or work outside the coffee growing areas and the second problem is directly related to the ability of coffee growers to develop innovations and technological change, which could eventually lead to these systems become unsustainable [22], in order to avoid these situations, public and private institutions should promote spaces for opportunities and make coffee production more attractive to encourage young people to continue improving and developing this productive activity, as an alternative to improve and diversify family income [23].

On the other hand, limited schooling (20% secondary; 18% higher) hinders technological adoption. Education, by facilitating the understanding of ecological processes and adaptive mechanisms, is key to sustainability; its absence tends to reduce the adoption of innovations and, therefore, sustainable performance [14,22,24], it is likely that for these reasons in group 2, which has a higher level of education, has higher levels of sustainability. However, accompaniment and training have proven to be factors that improve sustainability and yields in coffee farms [25,26], it is therefore recommended that Cooperativa La Prosperidad de Chirinos continue with training and ongoing technical assistance.

The indicators that showed significant differences between groups (total, wintering area and stubble area) show that farmers in group 2 have a larger land endowment, which corresponds to higher levels of sustainability. This association can be explained by historical, economic and social factors, as well as by the widely documented fact that a larger farm scale increases the margin to manage the territory, obtain economic benefits, diversify sources of income and access credit and technical services [27]. These differences point to the need to provide farmers with small farms access to credit, technical assistance and training programs that strengthen the adoption of sustainable practices without relying on territorial expansion.

The sustainability of productive systems depends on economic, environmental, and social components, which vary among coffee farms, with respect to the dimensions of sustainability evaluated, the environmental component the only criterion that resulted with values below the sustainability threshold was “soil quality” for Group 1 coffee farms. This may be explained by the fact that Andean landscapes tend to have steeper slopes [28], in addition, when analyzing the results of each indicator of the “soil quality” criterion, it was observed that the indicators “soil conservation techniques” and “slope” are the ones with a sustainability index lower than 3. These two indicators somehow complement each other, it is not possible to correct the slope of installed coffee farms, but different soil conservation techniques can be implemented and thus make coffee farms more sustainable; for example, conservation of native vegetation, construction of terraces and infiltration ditches, planting of live barriers, construction of dead barriers, planting design by contour lines, cover crops, crop diversification [29–33]. In addition, it is recommended that territorial management tools such as Suitability Watch Cajamarca (SWC) [28] be used to identify priority areas for intervention aimed at mitigating soil erosion, thus contributing to strengthening the environmental sustainability of coffee farms in the study area.

In the economic component, contrasts between criteria were observed. For agricultural economics, Group 2 showed a significantly higher performance (6.7 ± 2.3) compared to Group 1 (5.8 ± 2.8; $p = 0.0002$), suggesting a greater capacity for income generation and/or investment in farm management among producers with better endowments and access to services. In contrast, no statistically significant differences were detected in food sovereignty (G1: 5.9 ± 3.3; G2: 5.3 ± 2.4; $p = 0.438$), and both averages are slightly above the threshold but at low levels. This pattern is consistent with two elements of the context: the penalization implicit in the instrument in the face of low labor hiring and limited access to credit, conditions that are common among coffee farmers and that restrict operational and investment capacity; and the underutilization of intra prison diversification, which could improve household food availability without sacrificing the coffee system. Therefore, interventions should combine financial and labor inclusion (appropriate credit, extension services and rural employment) with diversification strategies aimed at enhancing food sovereignty [23,29].

The analysis of social sustainability contemplated one criterion: social aspects, in this the access to health services, education for children and basic services available to the coffee farm was analyzed. Group 1 showed higher values in this criterion associated with a higher level of education of the children, however this does not guarantee the sustainability of the farm since a large percentage of these young people who reach high school or university, develop their professional lives far from the place where coffee farming is developed [22,23]. In coffee specifically, succession is more likely when families can secure decent coffee income, land tenure, association/cooperative membership, and reliable access to family or hired labor conditions that lower the probability of permanent youth exit [30] there is a consensus that the participation of young people is fundamental for a resilient and sustainable coffee sector, being the generational relay that is vital to ensure the continuity of farms [22,23]. Therefore, the education becomes a lever for sustainability only when combined with youth retention strategies vocational training linked to the coffee value chain, access to land and credit, and cooperative based entrepreneurship that convert human capital gains into local farm succession rather than out migration [30,31].

The General Sustainability Index (GSI) for Groups 1 and 2 was above the threshold, with a consistent advantage for Group 2. Substantively, this indicates moderate overall performance: sustainability is maintained, yet bottlenecks persist, consistent with regional evidence [25,32,33]. In Cuba (UBPC La Herradura, Manicaragua, Villa Clara), studies report heterogeneous sustainability levels across farms—organizational and management advances coexist with soil related limitations and input constraints that depress aggregate scores [32]. In the Alto Mayo Valley (San Martín, Peru), the GSI applied to conventional vs. organic coffee shows higher environmental and social scores for organic systems [33]. Complementarily, evidence for Peruvian smallholders indicates that adopting sustainable agricultural practices (SAPs) is linked to productivity and technical efficiency gains provided these practices are supported by extension and access to finance [25]. Although all the referenced studies employ the General Sustainability Index (GSI), this study introduces an additional layer of analysis through cluster analysis, enabling the identification of homogeneous groups within the population and allowing the formulation of targeted, group specific recommendations to enhance the precision and applicability of sustainability interventions.

This study has limitations that should be considered when interpreting the findings. Several indicators rely on perception-based metrics which, despite standardized semantic anchors and trained surveyors, can introduce subjectivity. The cross-sectional design constrains inferences about temporal dynamics, and the geographic focus—though representative of northern Peru—may restrict generalization to other agroecological or socioeconomic contexts. The sustainability assessment also omitted explicit measures of fertilizer and pesticide use, potentially overlooking effects on environmental and agronomic performance, and the sample size was modest relative to the overall producer population, which may reduce statistical power and representativeness. Additionally, while the General Sustainability Index (GSI) offers an integrative overview, it does not capture key biophysical processes such as soil nutrient fluxes or long-term climatic influences. Future research should incorporate longitudinal monitoring, objective biophysical indicators, and spatial modeling to enhance the robustness and scalability of sustainability assessments.

5. Conclusion

The coffee farms of members of the Cooperativa Agraria Cafetalera La Prosperidad de Chirinos were classified into two groups with different sustainability levels. Group 2 achieved a higher overall sustainability index, whereas Group 1 despite surpassing the overall threshold fell below the threshold for the soil quality criterion. We also observed a potential generational constraint: the average farmer age exceeds 50 years, indicating limited generational replacement. In response, we recommend soil quality measures such as cover crops, live barriers, infiltration ditches, and contour planting. To address generational renewal, public and private institutions should create opportunities that make coffee production more attractive to younger people, while farming families are encouraged to pursue productive diversification as a pathway to food security. Finally, the assessment did not include fertilizer and pesticide use; future research should explicitly incorporate input use levels and evaluate their implications for sustainability.

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