Holistic sustainability in cattle ranching: A tri-dimensional framework for social, economic, and environmental resilience

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Abstract

Sustainability is a multidisciplinary concept that integrates social, economic, and environmental dimensions. To assess sustainability in production systems, this study employed a multidimensional approach, using indicators that reflect these three dimensions. The research focused on understanding the current dynamics of livestock farming by surveying 120 livestock farmers who provided prior consent. Indicators were quantified using a weighted scale, where values close to 10 represented the most desirable conditions, and values near 0 indicated the least desirable. The findings revealed key insights across the three dimensions. **Social dimension**: The age of the farmer emerged as a significant factor, with agricultural training playing a secondary role. **Economic dimension**: Annual yield and economic dependency on livestock farming were identified as critical factors y, **Environmental dimension**: Farm specialization, water availability, and soil erosion were highlighted as essential indicators for sustainable development. Additionally, a positive correlation was observed between these indicators. More experienced producers tended to rely more heavily on livestock farming for their income, achieving higher yields but often at the cost of intensive land use. These results underscore the need for balanced actions to promote sustainability, such as reducing social inequalities, diversifying animal production, supporting ongoing training for farmers, improving water management practices. In conclusion, achieving sustainability in livestock farming requires a holistic approach that balances social, economic, and environmental factors. Addressing these areas can enhance both the sustainability of production systems and the quality of life for livestock farmers.

Keywords: Agricultural training, Cattle, Economic dependency, Sustainable development, Silvopastoral systems, On-farm water

I. INTRODUCTION

Sustainability is a multidisciplinary [1,2] and systemic [3] concept that encompasses social, economic, and environmental dimensions. The integration of these dimensions gives rise to the triple bottom line approach [4], which serves as a foundational framework for assessing sustainability. Indicators that incorporate these three dimensions are employed to evaluate sustainability [2], thereby providing a comprehensive understanding of production systems and facilitating informed decision-making regarding the optimal allocation of resources [5]. Specifically, social indicators analyze aspects such as community organization, quality of life, and equity; economic indicators focus on factors such as profitability, liquidity, stability, and productivity; and environmental indicators address the management of natural resources and the balance between human needs and the capacity of the environment to meet those needs in the long term [6,7]. The overarching objective of sustainability is to ensure that production systems can fulfill present needs without compromising the well-being of future generations [8]. Furthermore, it aims to prevent the depletion of natural resources and the generation of irreversible damage to both the environment and the communities involved [7]. This holistic approach underscores the interdependence of social, economic, and environmental factors in achieving sustainable development.

Cattle farming is a critical component in the sustainable development of rural and urban communities [9]. Its significance stems from the intricate interplay between human populations and their surrounding ecosystems [3], as well as its contributions to economic stability, food security, and environmental stewardship [10]. Livestock production systems are broadly categorized into three types: (1) extensive systems, characterized by open grazing on pastureland's; (2) intensive systems, which utilize confined spaces and rely on externally supplied nutrients; and (3) mixed systems, which integrate elements of both extensive and intensive approaches [10]. Effective management of these systems necessitates practices such as controlled grazing and rotational rest periods for pastures, which enhance soil productivity and promote pasture recovery [11].

Recent research has highlighted the advantages of improved grasses over natural grasses, particularly due to their superior capacity for carbon (C) sequestration [12]. This attribute is increasingly relevant in the context of global climate change mitigation efforts. As a result, there is a growing trend toward replacing natural grasses with improved pastures where feasible, aiming to optimize productivity per unit area (m^2) and enhance C sequestration. Proper pasture management, including rapid rotational grazing, minimizes soil compaction by reducing the duration of cattle presence in any given area. This practice fosters improved soil conditions, which are essential for robust plant growth and increased forage availability for livestock [13]. Additionally, well-managed grazing systems reduce competition for nutrients among forage plants, promote dense grass cover, and mitigate losses in plant biodiversity and soil health. The integration of modern technologies, such as digitalization, remote sensing, precision livestock farming, and artificial intelligence, offers transformative potential for advancing sustainability in cattle farming [14]. Precision technologies and the automation of production processes—such as feeding and milking—enhance efficiency and reduce resource waste [15]. Furthermore, strengthening value chains and fostering government involvement are critical for improving the technical capacities of producers and ensuring the long-term sustainability of livestock systems [16, 17]. Animal welfare is another pivotal factor in sustainable livestock farming. Ensuring humane treatment reduces stress and the incidence of adverse events, thereby enhancing productivity and meat quality [18]. Compliance with animal welfare standards is also essential for obtaining certifications, such as those required for marketing organic meat, which increasingly influence consumer preferences and market.

On the other hand, enhancing the participation of all household members in agricultural activities is essential, particularly the inclusion of women, as their involvement plays a pivotal role in promoting diversification and reducing reliance on a single productive activity [19]. Furthermore, fostering collaboration and joint decision-making within families can significantly improve the management and coordination of agricultural tasks, leading to more efficient and sustainable outcomes [20]. The effective allocation of roles and responsibilities among family members also strengthens their commitment to shared family goals, thereby enhancing overall productivity and cohesion [21]. In addition, access to basic services—such as electricity, clean water, and sanitation—is critical for improving the quality of life for agricultural producers. These amenities not only enhance living conditions but also contribute to the efficiency and sustainability of farming operations. Finally, higher levels of education provide producers with the necessary training and management skills to address basic needs, adopt innovative practices, and improve their livelihoods [22].

Therefore, the objective of this study was to determine the sustainability of these systems using a tri-dimensional framework for social, economic, and environmental; seeking not only to understand the current dynamics of livestock, but also to identify determining indicators that must be strengthened to improve the quality of life of cattle producers.

II. MATERIALS AND METHODS

The study was conducted in cattle-raising districts located in the provinces of Jaén and San Ignacio, within the Cajamarca region. Specifically, the districts of Chontalí, Huabal, and Jaén in the province of Jaén, as well as Chirinos, Huarango, San Ignacio, and San José de Lourdes in the province of San Ignacio, were included in the analysis. These provinces exhibit diverse topographical features, with altitudes ranging from 333 to 3963 meters above sea level (m.a.s.l.) (Figure 1). The climate across the study area varies significantly, transitioning from cold conditions in higher elevations to humid tropical climates in the lowlands. Temperatures fluctuate between 11°C and 33°C, with an average annual rainfall of up to 1000 mm [23, 24].

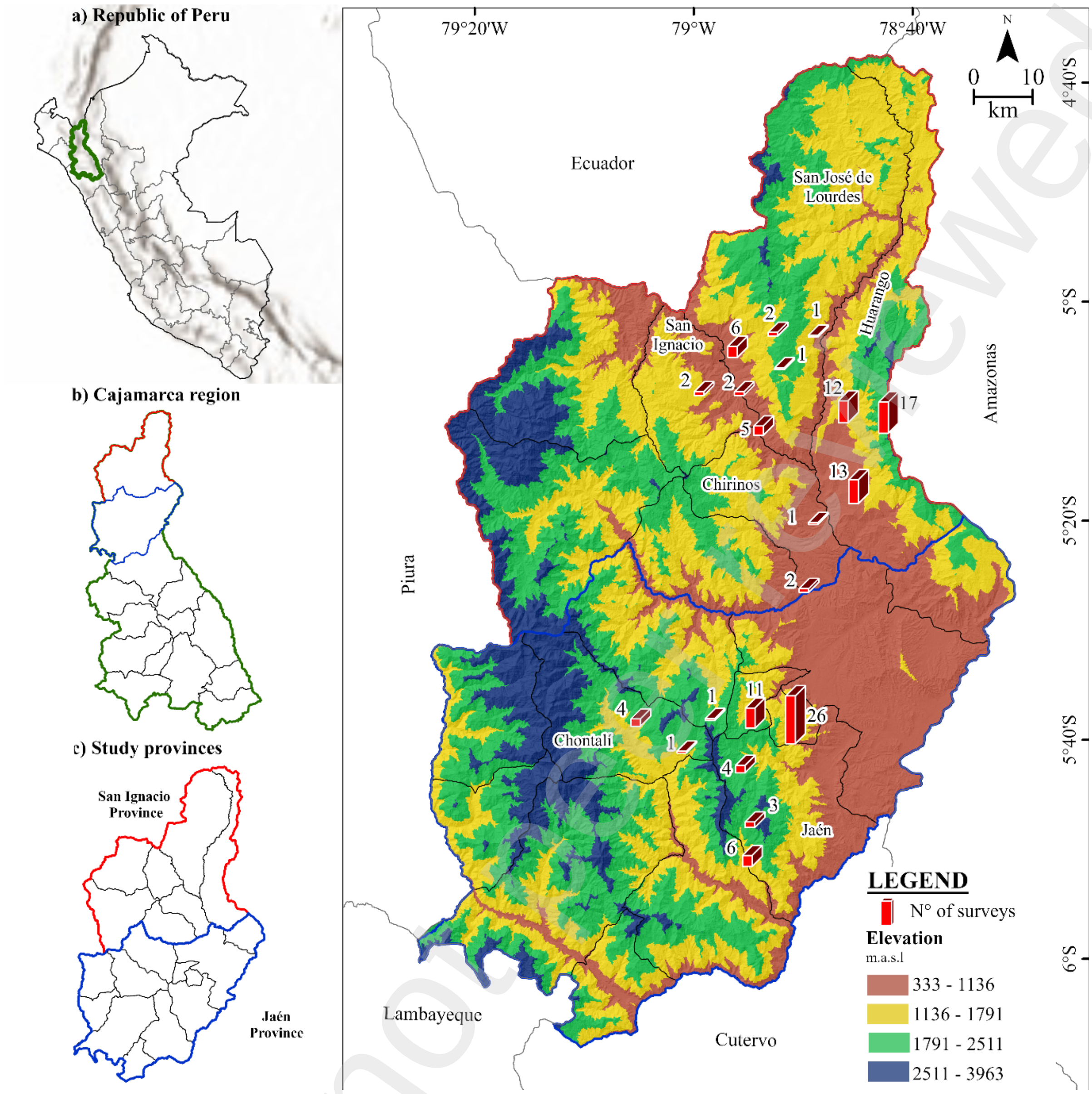

Figure 1. Location map of cattle farms in the province of Jaén and San Ignacio. This map was created by the authors using open access resources. The provincial and district boundaries were obtained from the Geoportal of the National Geographic Institute of Peru (IGN) (https://www.idep.gob.pe/geovisor/VisorDeMapas-3D/) in shapefile format with a DATUM WGS 1984. The map is for illustrative purposes only.

2.1. Population, sample, sampling

The study population consisted of 639 cattle ranchers registered in the Regional Management of Economic Development of the Provincial Municipality of Jaén and the Jaén San Ignacio Bagua-PEJSIB Special Project. From this population, a sample of 120 producers was selected using a probabilistic sampling method. This approach ensured that all livestock producers had an equal opportunity to be included in the study. Prior to data collection, verbal consent was obtained from each participant, and surveys were conducted in person to ensure accuracy and reliability in the responses.

2.2. Field Data Collection

The study was carried out between February and May 2024, and the surveys were administered directly and in person to 120 livestock producers. The survey included a total of 15 study variables (indicators), distributed in three dimensions (social, economic and environmental) [6,7]; of which 6 belong to the social dimension, 3 to the economic dimension and 6 to the environmental dimension (Table 1). The indicators were quantified using value weights, according to which values closer to 10 represented the most favorable or expected condition, and values closer to 0 represented the least desired condition.

For the conformation of the Basic Services variable (SERB), access to water, sewage and electricity was considered. The variable called Annual Yield (RENA) considered the total income generated by the farm in the previous year, calculated by adding the income derived from the sale of milk and cattle for meat production. They were assigned a score of 8, 4 and 2, respectively, according to the following conditions: a value of 8 for farms that exceed the average income; a value of 4 for farms that exceed the minimum wage that a person can earn in a year; and a value of 2 for farms with incomes below the annual minimum wage. The minimum living wage, as established by the Peruvian government, was S/1,025.00 per month. Revenue from the sale of cattle was calculated on the basis of the number of animals sold, the selling weight and the average price paid to the producer, which was determined at S/ 6.2 per kg of meat in live weight [25]. To calculate the income from the sale of milk, 305 days of lactation per cow per year were considered [26–28], the average daily milk production per cow (6.2 liters) [29] and the average price for 1 liter of milk paid to the producer (S/ 1.4) [25]. The environmental variable Farm specialization (ESPEX) is defined as the percentage of land dedicated to crop production. Consequently, farms with a higher level of specialization will have a greater proportion of their total ownership dedicated to livestock farming [6].

Table 1. Indicators for social, economic and environmental dimensions according to premise and weights of importance (score) established to determine the sustainability of livestock systems in Jaén and San Ignacio

DIMENSION	INDICATOR	PREMISE	SCORE	FOUNTAIN
Social	Rural Life (Distance in km) (VIR)	The finca is located 0 to 2 km from the nearest town with amenities	8	Proposed by the author based on the premise presented in [6]
		The farm is located 2 to 4 km from the nearest town with services	6	
		The farm is located 4 to 6 km from the nearest town with services	4	
		The property is >6 km from the nearest town with amenities	2	
	Basic Services (SERB)	The farm has 3 basic amenities	4	[6]
		The farm has 2 basic amenities	3	
		The farm has a basic service	2	
	Equity (EQUI)	Participation of women in relation ≥50% of farm workers	8	[6]
		Participation of women in relation <50% of farm workers	4	
		Non-participation of women in farm activities	2	
	Family Integration in Production and Decision-Making (IFPROD)	Decisions are made through mutual agreement among all family members	8	[6]
		Participation is exclusively permitted for the parent or head of household	6	
		Decisions are made only by the parent or head of the household out of habit or necessity	4	
		Decisions are made after external advice or market requirements	2	
	Agricultural training (CAPAGRI)	Always (participated in more than 3 trainings in the last year)	8	Proposed by the author based on the premise presented in [6]
		Sometimes (participated in at least 2 trainings in the last year)	4	
		Never (Did not participate in any training)	2	
	Agrarian affiliation	If you have agricultural affiliation	2	[6]
		He has no agrarian affiliation	1	

	(associativity) (FILA)			
Economic	Economic dependence on livestock activity (DECONAG)	Income from livestock activities that represented ≥50%	6	Proposed by the author
		Income from livestock activities that represented <50%	4	
	Annual Yield (RENA) (Total Income / Year / Farm)	Higher-than-average income	8	Proposed by the author based on the premise presented in [6]
		Income greater than the minimum wage in one year S/ 12,300.00	4	
		Income less than the minimum wage in one year S/ 12,300.00	2	
	Benefit/Cost Ratio (B/A)	Total Revenue/Cost of Production	Numerical variable	
Environmental	Availability and use of organic inputs (DUAO)	DUC= Availability and use of the peel, leaves and plant remains as fertilizers	2	[6]
		DUE= Manure availability and use	2	[6]
	Silvopastoral Systems (SPS)	More than 50% of its land has SPS	8	Proposed by the author based on the premise presented in [6]
		Less than 50% of your land has SPSs	6	
		Does not have SPS	4	
	Specialisation of the farm (ESPEX)	Range from 0 to 1 where the higher the degree of specialization, the greater the environmental sustainability	0 - 1	[6]
	Water on the farm (AGFI)	Drinkers	10	Proposed by the author based on the premise presented in [7]
		Pipes and/or hoses	5	
		Water springs, streams, streams, etc	1	
	Soil erosion (EROS)	Low (No soil loss due to rainfall or other weather conditions)	10	Proposed by the author based on the premise presented in [7]
		Moderate (surface soil dragging during rainy periods or when irrigating)	5	
		High (Landslides or loss of soil due to runoff during rainy periods)	1	
	Arable layer (CAPA)	Deep: Optimal arable layer for root development.	10	Proposed by the author based on the premise presented in [7]
		Moderate: Sufficient arable layer for crops.	5	
		Minimal: shallow or rocky soil	1	

2.3. Statistical analysis

A cluster analysis was conducted on non-normalized data employing the Ward method and Jaccard distance to classify producers into groups based on shared characteristics [7]. Additionally, the non-parametric Kruskal-Wallis test was applied to evaluate numerical variables across the generated groups. To ensure data compatibility, a standardization procedure was implemented, setting the mean to 0 and the standard deviation to 1 [30]. Subsequently, a Principal Component Analysis (PCA) was performed using the FactoMineR package in RStudio [31], aiming to identify the variables that contributed most significantly to the differentiation of these groups. Indicators with a loading ≥ 0.38 within the first five Principal Components (PCs) were selected for further analysis. The means of these selected indicators were then normalized to a range of 0 to 1 for each group using Max-Min linear normalization equations (Equation 1 for positive values and Equation 2 for cases where the expected positive value was not achieved) [6]. To assess the presence of significant differences among the indicators across groups, an analysis of variance (ANOVA) was conducted. Furthermore, a Sustainability Index (SI) was calculated following the methodology outlined by [6], and an independent samples t-test was utilized to compare the mean percentages between groups. A percentage scale was applied, categorizing values below 30% as unsustainable and values between 30% and 60% as indicative of low sustainability. Finally, a Spearman Correlation Analysis was performed using the Psych package in RStudio to eliminate redundant indicators derived from the PCA and to identify statistically significant correlations [7]. This comprehensive analytical approach ensured a robust evaluation of the data and facilitated the identification of key factors influencing group differentiation and sustainability.

Equation 1: Max-Min Linear Normalization

$$Vn = \frac{V - V_{min}}{V_{max} - V_{min}} \quad \text{(Equation 1)}$$

Equation 2: Inverse Normalization

$$Vn = 1 - \frac{V - V_{min}}{V_{max} - V_{min}} \quad \text{(Equation 2)}$$

Where:

Vn = Normalized Value
V = Observed value not normalized
Vmin = Minimum value of total data
Vmax = Maximum value of total data

III. RESULTS

The cluster analysis of non-normalized data using the Ward method with the Jaccard distance identified five distinct groups of producers based on their similarities, as illustrated in Figure 2. These groups reflect both geographical and productive characteristics, highlighting patterns among the farms. The non-parametric Kruskal-Wallis test was applied to the numerical variables, revealing significant differences between the groups. Key findings include: Group 2: This group consists of the youngest producers, with an average age of 41.39 ± 10.57 years. They have the smallest number of cattle (6.48 ± 4.05), the least property area (6.78 ha ± 5.47), and the smallest pasture area (3.28 ha ± 3.52). Group 5: In contrast, this group includes the oldest producers, with an average age of 58.52 ± 16.22 years. They have the largest number of livestock (25.89 ± 29.05), the most extensive property area (23.74 ha ± 26.66), and the largest pasture area (20.63 ha ± 24.31). These results, summarized in Table 2, demonstrate clear distinctions between the groups in terms of producer age, herd size, and land use, which are likely influenced by geographical and productive factors. The findings provide valuable insights for targeted interventions or support programs tailored to the specific needs of each group.

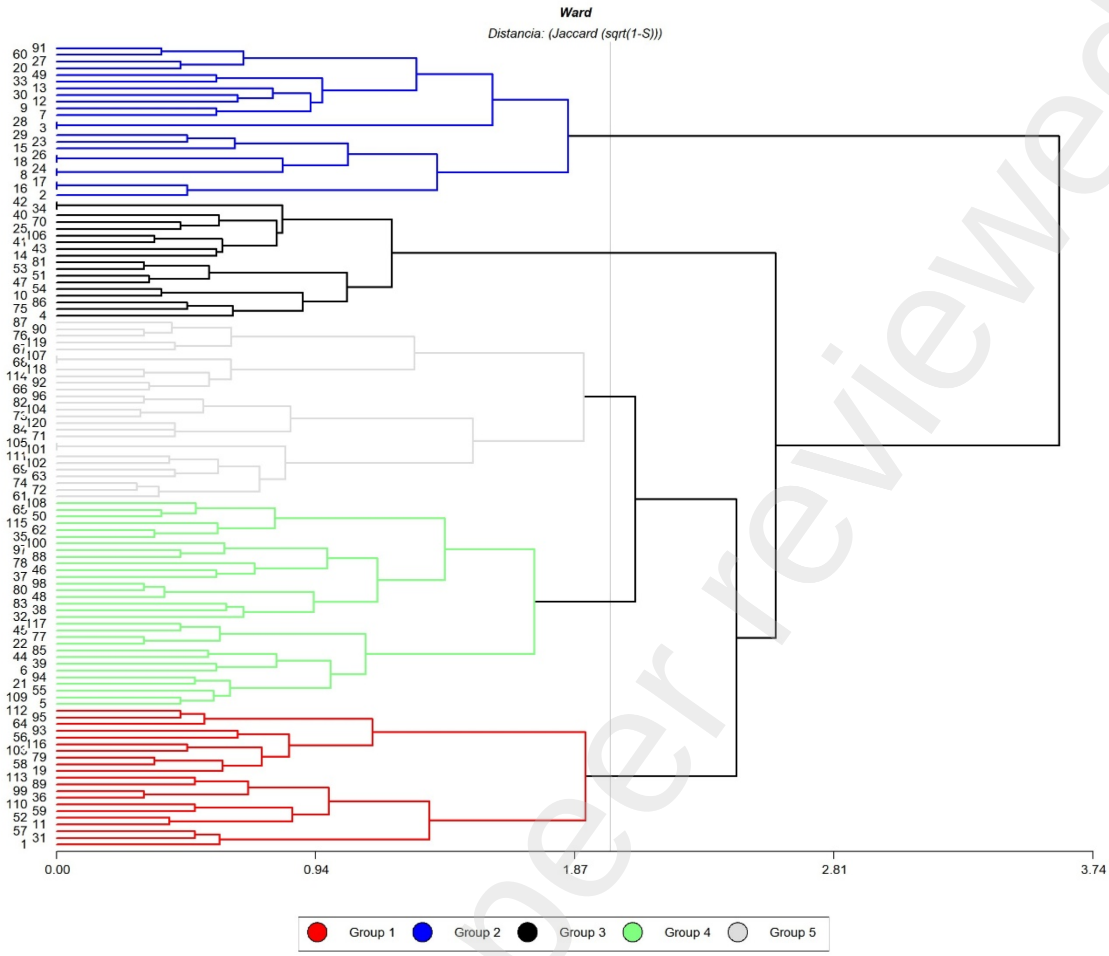

Figure_2. Formation of five clusters (groups) of cattle farms in the provinces of Jaén and San Ignacio using the Ward method with the Jaccard distance (Cophenetic correlation= 0.462): Group 1 (red), Group 2 (blue), Group 3 (black), Group 4 (green) and Group 5 (Lead)

Table 2. Means of the non-parametric Kruskal-Wallis test of the quantitative variables according to the groups generated.

Indicator	Group 1	Group 2	Group 3	Group 4	Group 5
AGE *	49.9 ± 13.58 bc	41.39 ± 10.57 a	53.22 ± 12.16 bc	50 ± 12.08 b	58.52 ± 16.22 c
Total Cattle *	12.19 ± 17.32 a	6.48 ± 4.05 a	23.22 ± 21.96 b	21.13 ± 26.68 b	25.89 ± 29.05 b
Cows *	7.48 ± 13.49 a	3.7 ± 2.36 a	12.28 ± 15.57 b	11.35 ± 16.02 b	13.93 ± 16.5 b
Total property *	16.76 ± 42.78 ab	6.78 ± 5.47 a	20.22 ± 33.55 abc	18.06 ± 25.32 bc	23.74 ± 26.66 c
Pasture area *	8.31 ± 10.92 b	3.28 ± 3.52 a	13.17 ± 21.33 bc	13.19 ± 16.26 bc	20.63 ± 24.31 c

Means with different letters are significantly different (p > 0.05).

The PCA showed the formation of 14 PCs of which the first 10 were selected, representing more than 85.48% of the cumulative variance (Figure_3). It was possible to extract 5 social variables, 2 economic variables and 3 environmental variables. Social variables (5): These include factors such as the age of the producer (AGE) and the specialization of the farm (ESPEX), which reflect social aspects of the agricultural context. Economic variables (2): These include economic dependence on agricultural activity (DECONAG), highlighting the financial reliance on farming and environmental variables (3): These variables likely relate to land use or ecological factors, though they are not explicitly named in the provided text. PC 1: The most influential variables were the economic variable DECONAG (Economic dependence on agricultural activity) and the social variable AGE (age of the producer). This suggests that the economic reliance on agriculture and the age of the farmer are significant drivers of the first principal component. PC 2: The social variable ESPEX (Specialization of the farm) was the most prominent. This indicates that farms with more pasture areas relative to total land area play a significant role in shaping the second principal component. The prominence of AGE and DECONAG in PC 1 suggests that older producers and those more economically dependent on agriculture are key factors in the dataset's variability, and the influence of ESPEX in PC 2 highlights the importance of farm specialization, particularly the proportion of pasture areas, in differentiating the data.

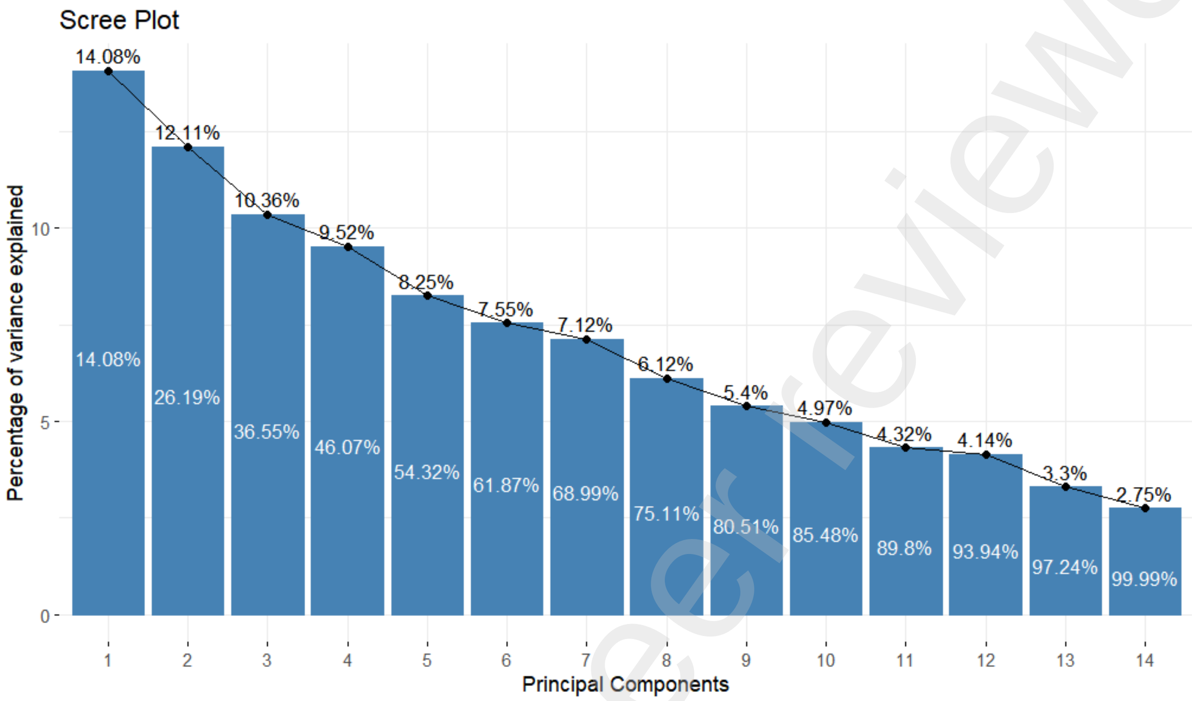

Figure_3. Scree plot, a result of the PCA, showing the percentage of variance for each principal component (data on the bars) and the cumulative variance (data within the bars).

Table 3. Selection of the most influential variables of the first 5 CPs according to their weight of importance within the CP.

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
AGE	**-0.38741**	0.193682	0.280567	0.005654	-0.16404	-0.05087	-0.36756	-0.01018	0.205972	-0.47501
VIR	-0.00353	0.061230	-0.11384	0.090821	0.231769	0.784753	0.093687	0.478963	0.127807	-0.19572
SERB	-0.16264	-0.24871	-0.28637	-0.23830	**0.483212**	0.190802	-0.0815	-0.48077	-0.21543	0.06296
EQUI	-0.22329	0.304668	0.193442	-0.20547	**0.397249**	-0.03845	-0.48546	0.013880	-0.08400	-0.03813
IFPROD	-0.04677	0.35649	0.299761	-0.0200	-0.11265	0.40972	0.1849	-0.53282	0.322215	0.23817
CAPAGRI	-0.05165	0.3656	-0.19031	0.162149	**0.392854**	-0.32508	0.418695	0.003073	0.270503	-0.06179
FILA	0.047851	0.070272	-0.2791	**-0.58676**	-0.12664	-0.08842	0.273820	-0.07764	0.262945	-0.49763
DECONAG	**-0.45839**	-0.33353	0.165793	-0.09602	-0.05715	-0.07166	0.207694	0.295783	0.033340	0.05053
RENA	-0.19100	-0.18319	**0.460423**	-0.23274	0.390772	-0.11648	0.297710	0.144978	0.141067	0.19577
SSP	-0.30383	0.270840	-0.01418	-0.29128	-0.24505	0.135539	0.290036	0.022712	-0.66263	-0.01567
ESPEX	-0.35562	**-0.38554**	0.020123	0.21343	-0.24199	0.120394	0.124806	-0.29135	0.173295	-0.07675
AGFI	-0.30316	0.328168	-0.07729	**0.469932**	0.040614	-0.10082	0.209933	-0.02080	-0.22332	-0.03031
EROS	-0.37811	-0.12701	**-0.46226**	0.193387	0.097260	-0.01429	-0.14658	-0.05422	0.123295	-0.06516
CAPA	-0.25727	0.218498	-0.35381	-0.26411	-0.24356	-0.0196	-0.17976	0.227887	0.294022	0.60851

AGE Indicator: Significant differences were observed between Group 2 and Group 5. This suggests variations in age-related factors (e.g., population age distribution, workforce age, etc.) that may influence social sustainability. Overall Performance: The social dimension shows a balanced performance across groups, indicating that while there are differences, no single group dominates or lags significantly in this area. Economic dimension, DECONAG Indicator: Significant differences were found between Group 1 and Group 5, highlighting disparities in economic activities or dependencies. RENA Variable, significant differences were observed between Group 3 and Group 5, suggesting variations in economic performance or resource allocation. This group stands out in the economic dimension, likely due to its higher dependence on livestock activity, which contributes to its higher income compared to other groups. Environmental dimension, ESPEX Indicator: Significant differences were found among Groups 1, 3, and 5, indicating variations in environmental practices or impacts. AGFI Indicator, significant differences were observed among Groups 2, 3, and 5, suggesting disparities in agricultural or environmental sustainability efforts. This group excels in the environmental dimension, indicating stronger environmental practices or policies compared to other groups. Sustainability Index, groups 1 and 2: Both groups showed low levels of sustainability, with indices below 60%. This suggests that these groups may need targeted interventions to improve their sustainability across social, economic, and environmental dimensions. Groups 3 to 5: These groups demonstrated higher sustainability indices, all above 60%. and, group 3 achieved the highest Sustainability Index (64.03%), driven by its strong economic performance, particularly its reliance on livestock activity, which generates higher income compared to other groups (Table 4, Figure 4).

Table 4. Analysis of variance of the normalized indicators and comparison of the sustainability index for each group.

Dimension	**Normalized indicator**	**Group 1 (21)**	**Group 2 (23)**	**Group 3 (18)**	**Group 4 (31)**	**Group 5 (27)**
Social	AGE *	0.4985 ab	0.3655 a	0.5503 b	0.500 ab	0.6331 b
	SERB	0.7857 a	0.8261 a	0.8333 a	0.9032 a	0.8704 a
	TEAM	0.873 a	0.8986 a	0.9259 a	0.8817 a	0.9506 a
	CAPAGRI	0.2698 a	0.2609 a	0.1481 a	0.1935 a	0.2099 a
	ROW	0.381 a	0.3478 a	0.1667 a	0.1613 a	0.1481 a
	Mean	**0.5616**	**0.5398**	**0.5249**	**0.528**	**0.5624**
Economic	DECONAG *	0.3333 a	0.6522 ab	1.000 bc	0.871 bc	0.7407 c
	RENA*	0.4286 ab	0.4928 ab	0.6481 b	0.4731 ab	0.2346 a
	Mean	**0.381**	**0.5725**	**0.8241**	**0.672**	**0.4877**
Environmental	ESPEX *	0.4463 a	0.6106 ab	0.6598 b	0.7803 bc	0.9191 c
	AGFI *	0.4286 ab	0.3188 a	0.358 a	0.4731 ab	0.6543 b
	EROS*	0.4921 a	0.4444 a	0.6975 ab	0.8566 b	0.856 b
	Mean	**0.4556**	**0.458**	**0.5718**	**0.7034**	**0.8098**
Group 1	Percentage mean	**46.61%**				
Group 2	Percentage mean		**52.34%**			
Group 3	Percentage mean			**64.03%**		
Group 4	Percentage mean				**63.45%**	
Group 5	Percentage mean					**62.00%**

Variables with * are statistically significant. Means with different letters are significantly different (Tukey $p < 0.05$)

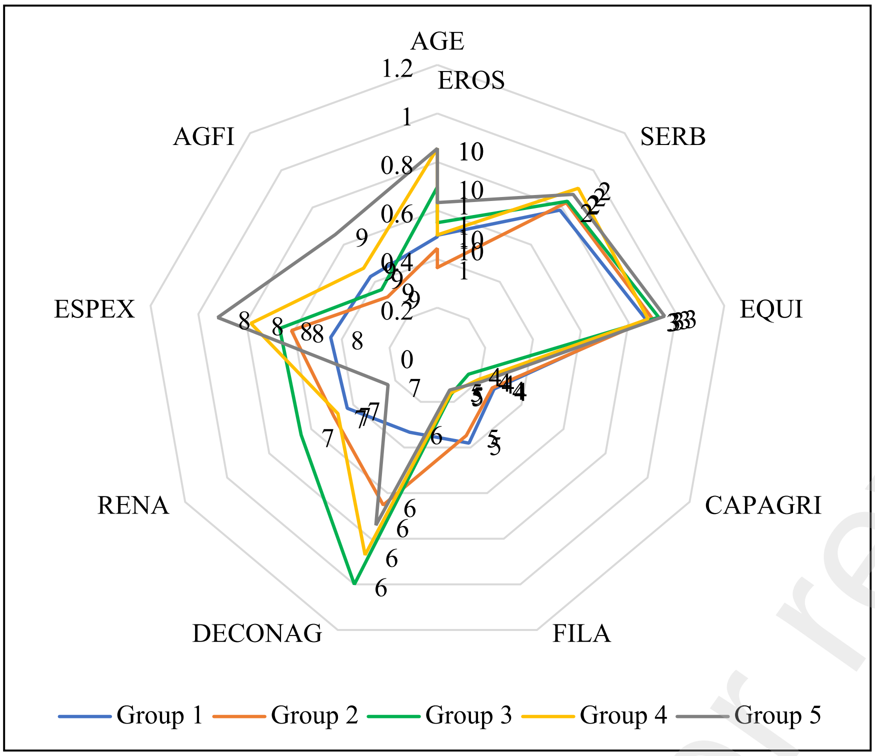

Figure_4. Radial graph of the means of the variables according to the social (AGE, SERB, EQUI, CAPAGRI, FILA), economic (DECONAG, RENA) and environmental (ESPEX, AGFI, EROS) dimensions; of the 5 groups of producers.

Spearman's Correlation analysis revealed that the most influential indicators were AGE, DECONAG, RENA, ESPEX, CAPAGRI, AGFI and EROS (Figure_5). These results coincide with the PCA of dimensions 1 and 2 where the indicators with the greatest contribution to PC formation are shown (Figure_6). Spearman's Correlation analysis showed positive correlations (***) between Economic Dependence on Agricultural Activity (DECONAG) and Production Specialization (ESPEX) (0.35), DECONAG and Annual Yield (RENA) (0.34). Also, positive correlations (**) were identified between Agricultural Training (CAPAGRI) and Water on the Farm (AGFI) (0.28); and Production Specialization (ESPEX) and Soil Erosion (EROS) (0.25). In addition, positive correlations (*) were observed between AGFI and EROS (0.21), AGE and DECONAG (0.20); as well as between ESPEX and Capa Arable (CAPA) (0.20). However, a negative correlation was observed between SERB and AGE (-0.14), although it was not statistically significant; suggests that, as the age of producers increases, they have less access to basic services (Figure_5).

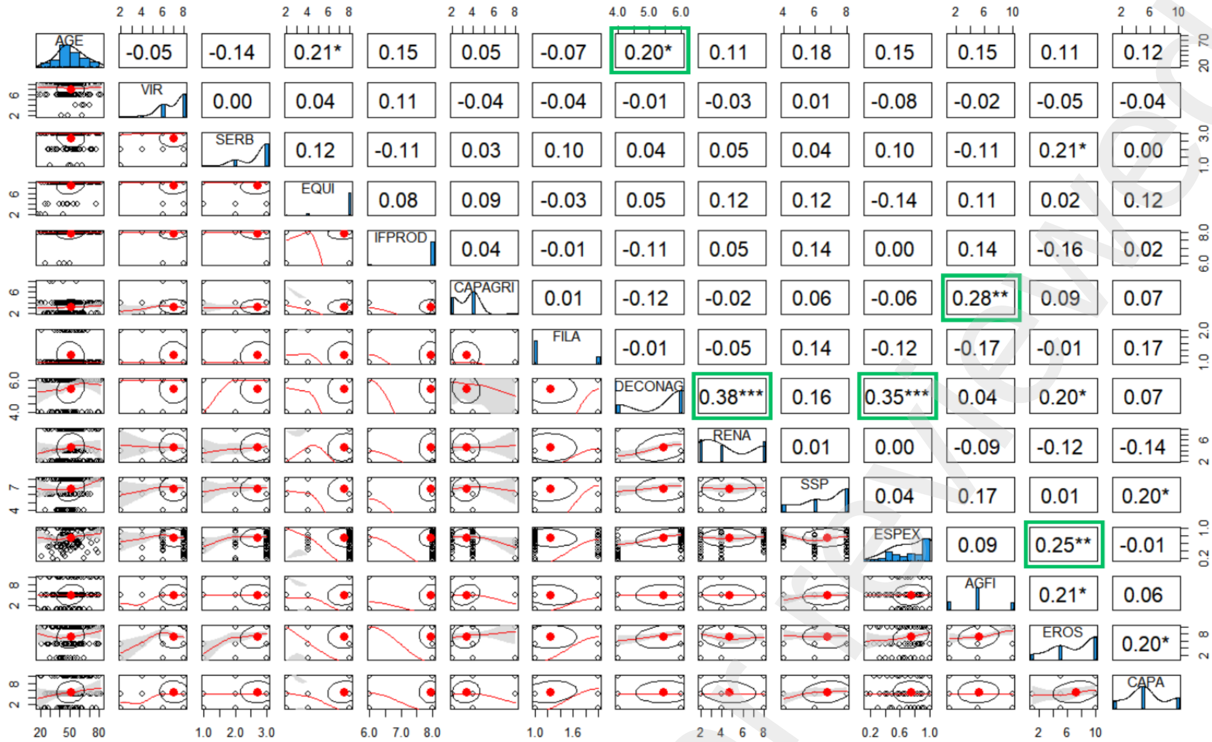

Figure_5. Spearman Correlation Analysis to eliminate redundant indicators resulting from the PCA.

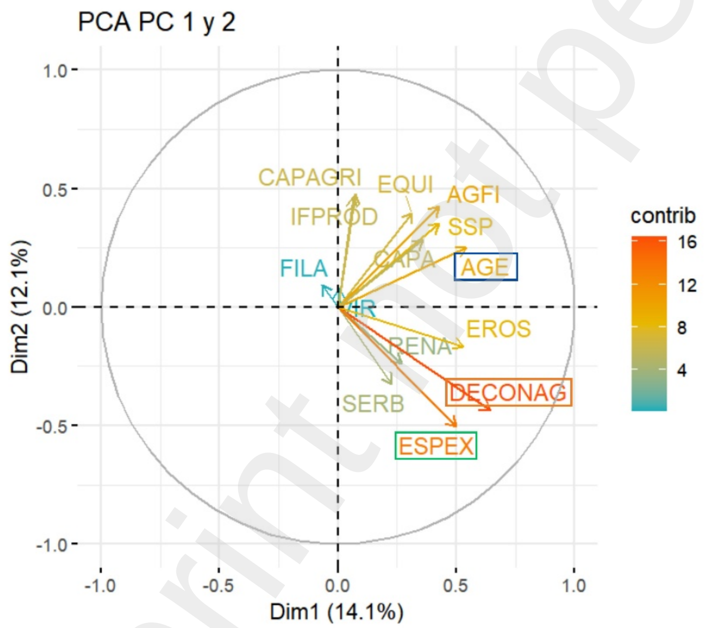

Figure_6. Most influential indicators in major components 1 and 2: social (blue box), economic (orange box) and environmental (green box) indicators. The vectors are represented by a color scale ranging from blue to red, which represents the magnitude of this contribution.

IV. DISCUSSION

The analysis of the sustainability of livestock systems revealed a strong predominance of environmental variables. A positive and highly significant correlation was observed between Economic Dependence on Agricultural Activity (DECONAG) and Production Specialization (ESPEX). This suggests that farms with a larger proportion of pasture area relative to their total property area—indicating higher specialization—tend to exhibit greater economic reliance on livestock activities [6]. Furthermore, a significant positive correlation was identified between DECONAG and Annual Yield (RENA), implying that higher economic income is associated with increased economic dependence on livestock production. This relationship may reflect a scenario where farms with higher incomes allocate more resources and labor to maximize annual returns, potentially leading to greater economic dependence on acquiring inputs and sustaining this productive activity [32]. However, such reliance on a single economic activity may heighten vulnerability to market fluctuations or external adversities, such as droughts, which could significantly reduce profitability. In contrast, diversifying production systems—for instance, by incorporating value-added processes for milk and meat—could mitigate risks and promote more sustainable and profitable livelihoods for producers [33]. Additionally, notable differences were observed between demographic groups in terms of age and resource availability. Younger producers were found to have fewer resources compared to older producers, who typically own more livestock, land, and pasture. Nevertheless, younger producers demonstrated a greater propensity for innovation and adoption of new technologies in livestock farming, which could enhance productivity and sustainability in the long term [34].

Similarly, a positive and statistically significant correlation was observed between Production Specialization (ESPEX) and Soil Erosion (EROS). This suggests that an increase in pasture area relative to the total property area is associated with a higher risk of soil erosion. This phenomenon can likely be attributed to the irregular topography of the farms, as soil erosion tends to be more pronounced in areas with steeper slopes [11]. To address this issue, farmers may adopt practices aimed at mitigating soil erosion, such as implementing Silvopastoral Systems (SPS) and livestock rotation strategies [35]. Although the Agricultural Training (CAPAGRI) indicator was not statistically significant, it exhibited a positive correlation with Water Availability on the Farm (AGFI). This indicates that higher levels of agricultural training are associated with increased efforts to improve water availability on farms. Consequently, farmers with greater educational attainment are more likely to invest in new technologies and resource management practices [22], which can positively influence pasture quality and livestock production.

A positive and statistically significant correlation was observed between Water Availability on the Farm (AGFI) and Soil Erosion (EROS), indicating that increased water availability is associated with higher levels of soil erosion. This relationship may be attributed to the intensification of agricultural practices facilitated by greater water access, which can exacerbate soil erosion if proper pasture management strategies are not implemented. Notably, the highest levels of runoff and soil loss are typically observed in uncovered soils, whereas croplands and pastures with adequate vegetation cover exhibit the lowest erosion rates [36]. Additionally, a positive and moderately significant correlation was identified between Soil Erosion (EROS) and Arable Land Capacity (CAPA), suggesting that increased arable cover is also associated with elevated soil erosion. This finding may reflect the impact of intensive agricultural activities, combined with environmental factors such as rainfall, wind, and land slope, which collectively contribute to soil erosion by facilitating runoff [11].

Additionally a positive and moderately significant correlation was observed between Silvopastoral Systems (SPS) and Arable Land Capacity (CAPA), indicating that the integration of SPS in livestock farms contributes to the improvement of topsoil quality. Specifically, the combination of trees, grasses, and livestock within the same production system enhances soil organic matter content, improves soil structure, and stabilizes the soil through the root systems of trees and shrubs. These factors collectively reduce soil erosion [37]. The presence of SPS exerts a beneficial influence on the arable soil layer by enhancing its structure and organic matter content, which are critical for maintaining productivity and ensuring the long-term sustainability of livestock farming systems. The adoption of SPS reflects a growing trend toward environmentally sustainable practices, which are essential for natural resource conservation and climate change mitigation [38]. Furthermore, the provision of shade through living fences and scattered trees underscores farmers' recognition of the importance of animal welfare, highlighting the multifaceted benefits of SPS implementation [39].

On the other hand, a positive correlation was identified between the age of producers (AGE) and Economic Dependence on Agricultural Activity (DECONAG), suggesting that older producers tend to exhibit greater economic reliance on livestock activities. This trend may be associated with a reduction in farm size and declining incomes as producers age [40]. Additionally, a negative correlation though not statistically significant—was observed between AGE and Access to Basic Services (SERB), indicating that older producers often face challenges in accessing essential services [41]. This presents a significant challenge for public policy, as this demographic represents a vulnerable population requiring prioritized attention. Furthermore, it is important to note that while improving living conditions is a critical objective, other studies have demonstrated that such improvements, if not managed sustainably, can lead to unintended consequences, such as a reduction in biodiversity [6].

The present study encountered certain limitations, primarily due to the multidisciplinary nature of sustainability, which necessitates the integration of diverse dimensions and disciplines. Additionally, each production system and geographical region exhibits unique characteristics that require specific attention. A recurring issue observed across most livestock farms was the limited availability of water for both livestock and pasture production. This highlights a critical area for future research and intervention. Subsequent studies should prioritize the development and implementation of strategies aimed at improving the efficient management of water resources. Such strategies should incorporate innovative technologies tailored to the specific realities of different geographical areas, ensuring their adaptability and effectiveness. Addressing these challenges is essential for promoting the long-term sustainability of livestock systems.

V. CONCLUSIONS

The findings of this study elucidate the principal indicators influencing the sustainable development of cattle farming, delineating their implications across social, economic, and environmental dimensions. Within the **social dimension**, the age of the producer emerged as a statistically significant factor, while agricultural training was identified as a secondary yet relevant variable. In the **economic dimension**, annual performance and the degree of economic dependence on livestock farming were determined to be critical determinants. Regarding the **environmental dimension**, farm specialization, water availability, and soil erosion were found to be pivotal factors. A statistically significant positive correlation was observed between the age of the producer, agricultural training, economic dependence on livestock, economic performance, and the intensive utilization of land for pasture production. This interrelationship suggests that producers with greater experience tend to exhibit a higher reliance on livestock farming as their primary income source, achieve superior economic performance, and adopt more intensive land-use practices. Therefore, to advance sustainability in these critical areas, the following strategic actions are recommended: (1) addressing social inequalities and enhancing access to essential services for vulnerable populations; (2) diversifying animal-derived products, such as dairy and meat, to add value and mitigate economic dependence on a single revenue stream; (3) promoting continuous training and education programs for producers to enhance their technical and managerial capacities; and (4) fostering the adoption of sustainable practices, including silvopastoral systems and improved water resource management techniques.

Author Contributions

Josué Tafur-Culqui: Conceptualization, data curation, formal análisis, investigation, methodology, visualization, writing – original draft, writing – review and editing. Agree to be responsible for all aspects of the work to ensure that issues related to the accuracy or completeness of any part of the work are properly investigated and resolved.

Darwin Gómez-Fernández: Methodology, writing – review and editing. Drafting of the paper or critical revision of the paper for important intellectual content.

Juancarlos Cruz-Luis: Funding acquisition, project administration, supervision.

Daniel Tineo: conceptualization, data curation, methodology, supervision, validation, writing – review & editing. Agrees to be responsible for all aspects of the work to ensure that issues related to the accuracy or completeness of any part of the work are properly investigated and resolved.

Victor H. Taboada-Mitma: Funding acquisition, project administration, resources, supervision. Draft the paper or critically review it for important intellectual content.

Rosalía Quichua-Baldeón: Methodology, writing – review and editing. Drafting of the paper or critical revision of the paper for important intellectual content.

Marielita Arce-Inga: Methodology, writing – review and editing. Drafting of the paper or critical revision of the paper for important intellectual content.

Janella Anchayhua: Methodology, writing – review and editing. Drafting of the paper or critical revision of the paper for important intellectual content.

Raúl Rabanal-Oyarse: Methodology, writing – review and editing. Drafting of the paper or critical revision of the paper for important intellectual content.

Malluri Goñas: Conceptualization, methodology, project administration, supervision, validation, writing – review and editing. Drafting of the paper or critical revision of the paper for important intellectual content.

Acknowledgment

The authors would like to thank the Instituto Nacional de Innovación Agraria (INIA) through the Investment Project with CUI N° 2472675: "Mejoramiento de los servicios de investigación y transferencia de tecnología agraria en la estación experimental agraria Baños del Inca en la localidad de Baños del Inca del distrito de Baños del Inca - provincia de Cajamarca - departamento de Cajamarca", which financed the execution of the research. They also thank Leiser Huanca, Javier Muñoz, David Coronado, Yolmer Dávila, Yadhira Olano and Larry Dusty for obtaining information for this study.

Declaration of conflict of interest

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

Funding sources

This research was financed by the Instituto Nacional de Innovación Agraria INIA through an Investment Project with CUI N° 2472675 "Mejoramiento de los servicios de investigación y transferencia de tecnología agraria en la estación experimental agraria Baños del Inca en la localidad de Baños del Inca del distrito de Baños del Inca - provincia de Cajamarca - departamento de Cajamarca".

Ethical Statement

This study consisted of face-to-face surveys of farmers (interviewer to respondent), which allowed the collection of the descriptive data necessary for the research, with all respondents being of legal age. Participation in the survey was voluntary and informed verbal consent was obtained from all participants prior to their inclusion in the study, as the data collected were used exclusively for the conduct of the research, and as no tissues, biological samples, or experimental interventions were used, this study does not require additional ethical considerations beyond those related to the confidentiality of the survey and voluntary participation of the respondents. The methodology of the study was reviewed and approved by the research area of the Investment Project with CUI No. 2472675: "Mejoramiento de los servicios de investigación y transferencia de tecnología agraria en la estación experimental agraria Baños del Inca en la localidad de Baños del Inca del distrito de Baños del Inca - provincia de Cajamarca - departamento de Cajamarca”

Declaration of generative AI and AI-assisted technologies in the writing process.

During the preparation of this work, the authors used ChatGPT to improve the writing and readability of the manuscript, which was then meticulously revised and edited. The authors take full responsibility for the content.

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