

Multivariate characterization and typology of cattle production systems in the high jungle of Peru: Insights for improving sustainability and productivity

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ABSTRACT

Background: In Peru's high tropical region, cattle production systems exhibit low productivity, largely due to heterogeneous management practices influenced by diverse environmental and socioeconomic conditions.

Aim: This study aims to categorize cattle production systems in the Peruvian high jungle using multivariate analysis. This allows us to identify three distinct production systems with significant socioeconomic and technological differences.

Methods: A survey was conducted among 210 cattle producers from the districts of Oxapampa, Chontabamba, and Huancabamba, located in the Pasco department (Peru). Categorical principal component analysis (CATPCA) and hierarchical cluster analysis (HCA) were applied to group farms with similar productive features. This classification produced meaningful typologies that can inform tailored management practices and policy decisions.

Results: CATPCA explained 22.46% of the total variance, identifying milk production, cattle dosing, and cow culling age as key factors. HCA revealed three distinct production systems that differed significantly ($p < 0.05$) across social, farm and pasture management, animal production, and economic-financial components: (1) Traditional Extensive System representing 17.14% of producers, characterized by low educational level and limited technology use. Farms are small, rely mainly on natural pastures, experience high pest incidence, and have low milk yield (36–50 L/day), with production primarily destined for self-consumption; (2) Improved Dual-Purpose Extensive System comprising 78.09% of producers, characterized by intermediate level of educational and technology adoption, diversified farm activities, effective pest control, moderate milk production (60–80 L/day), and varied milk marketing destination; and (3) Semi-Intensive System 4.77% of producers, characterized by higher education levels, mixed land use, aging pastures, high milk yield (140–150 L/day), and milk marketed mainly to dairy plants.

Conclusion: The distinct characteristics of each system highlight the need for regional livestock extension programs that combine technical training, knowledge exchange, and participatory innovation with remote sensing and geospatial tools to monitor pastures, stocking rates, water resources, and land-use changes.

Keywords: Categorical principal component analysis, Cattle production systems, Farm stability and resilience, High tropical.

Introduction

Cattle production systems in Peru's high tropics represent a complex interaction between environmental (altitude, precipitation, and soil properties), biological (forage species, pest and disease prevalence, and genetic potential), and socioeconomic (land tenure, credit access, technical assistance, and market linkages) factors. The dynamics of soil, plants, and animals are

fundamental to the productivity and sustainability of these systems. However, the socioeconomic conditions of the producers, which determine the inputs, processes, and outputs of the system, deeply influence the management of these components (Maicelo and Bardales, 2017). Understanding this interplay is crucial because it directly links local cattle production to

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broader global challenges, including food security and climate change.

The systemic approach to cattle production in South America is relatively recent from a conceptual perspective. These systems are highly dynamic and exhibit various definitions and characteristics (Sekaran *et al.*, 2021). In the Pasco department, livestock production systems are distinguished by their heterogeneity and non-standardized traditional practices, resulting in low yields and negative effects on producers' profitability and living conditions (Sánchez *et al.*, 2019; Rodríguez *et al.*, 2023).

Understanding the interrelationship among the components of production systems is essential for identifying management patterns that facilitate informed decision-making. Multivariate analysis, an advanced statistical tool, allows simultaneous examination of multiple variables, providing a comprehensive view of the complex relationships that define these systems (Palacio *et al.*, 2020). This methodology has proven effective for the productive characterization of systems in the Pasco department's high tropics, enabling the identification of differentiated productivity levels and highlighting the need for technical interventions aimed at improving efficiency (Rodríguez *et al.*, 2022). Principal component analysis (PCA) combined with hierarchical cluster analysis (HCA) are the most common methods for these investigations, although their use is limited to numeric variables (Argüelles *et al.*, 2014; Cruz *et al.*, 2023). However, when evaluating cattle production systems in tropical regions, differences among farms, such as the type of grasses used, pest incidence, or pasture management practices, are not only quantitative but often categorical. Categorical principal component analysis (CATPCA), complemented by HCA, enables the joint analysis of quantitative and qualitative variables, potentially yielding more realistic regional classification of production systems than those obtained with methods restricted exclusively to numerical variables (Torres *et al.*, 2021; Wairimu *et al.*, 2021).

Although CATPCA has been proposed as a valuable tool for classifying heterogeneous and complex systems (Li *et al.*, 2022), its effectiveness relative to traditional PCA has not been empirically tested, and no studies have compared both methods in livestock systems with mixed data types (Itafa and Onto, 2022). Therefore, while CATPCA constitutes a viable alternative, its superiority cannot be assumed without explicit validation.

This lack of comparative assessment adds to the scarcity of recent typological studies on cattle production systems in the Peruvian high tropics and Latin America. Previous studies have mainly described productive characteristics without establishing data-driven typologies that integrate socioeconomic and management variables (Müller, 2005; Sánchez *et al.*, 2019; Tongo and Soplin, 2022).

Consequently, the understanding of structural diversity and underlying factors influencing the productivity of these systems remains limited. This study addresses these gaps by applying CATPCA and HCA to develop an evidence-based typology of cattle production systems in the Peruvian high tropics, providing novel insights into their organization and performance. However, no formal comparison between CATPCA and PCA has been performed, which remains an open methodological question for future research.

In this context, this study aimed to categorize cattle production systems in the high tropics of Peru using multivariate analysis based on socioeconomic and productive indicators. This approach allowed us to identify distinct production systems with significant socioeconomic and technological differences. Therefore, we identified management patterns and key factors determining productivity, providing a solid basis for designing strategies aimed at improving these systems' sustainability and efficiency.

Materials and Methods

Area of study

The study was conducted in the districts of Oxapampa, Chontabamba, and Huancabamba, in the province of Oxapampa, Pasco department, Peru (Fig. 1). This area is part of the Peruvian Central Selva and is characterized by a diverse topography ranging from the tropics edge to the high tropics, with altitudes between 1,000 and 3,500 m above sea level (SENAMHI, 2019). The predominant climate in the region is humid and semi-warm, with temperatures between 16°C and 23°C. The rainy season, which runs from November to March, generates high relative humidity, which fluctuates between 80% and 90%, favoring lush and diverse vegetation.

According to Holdridge's (2000) life zone classification, the region is mainly composed of very humid lowland tropical montane forest (bmh-MBT) and very humid tropical montane forest (bmh-MT). High rainfall and moderate temperatures characterize these areas, offering an ideal environment for the proliferation of ecosystems rich in flora and fauna, which strengthens their environmental value. The ecological and climatic heterogeneity of the Oxapampa, Chontabamba, and Huancabamba districts creates optimal conditions for cattle production system development. Therefore, their characterization is essential for designing strategies aimed at the implementation of sustainable livestock management practices to improve the productive and economic efficiency of cattle production systems in this region (Rodríguez *et al.*, 2022).

Sample selection

Stratified random sampling was performed using three districts of the province of Oxapampa as strata. To determine the sample size, the following formula

was applied:
$$n = \frac{Z^2 * p * q * N}{E^2 * (N - 1) + Z^2 * p * q}$$
, where:

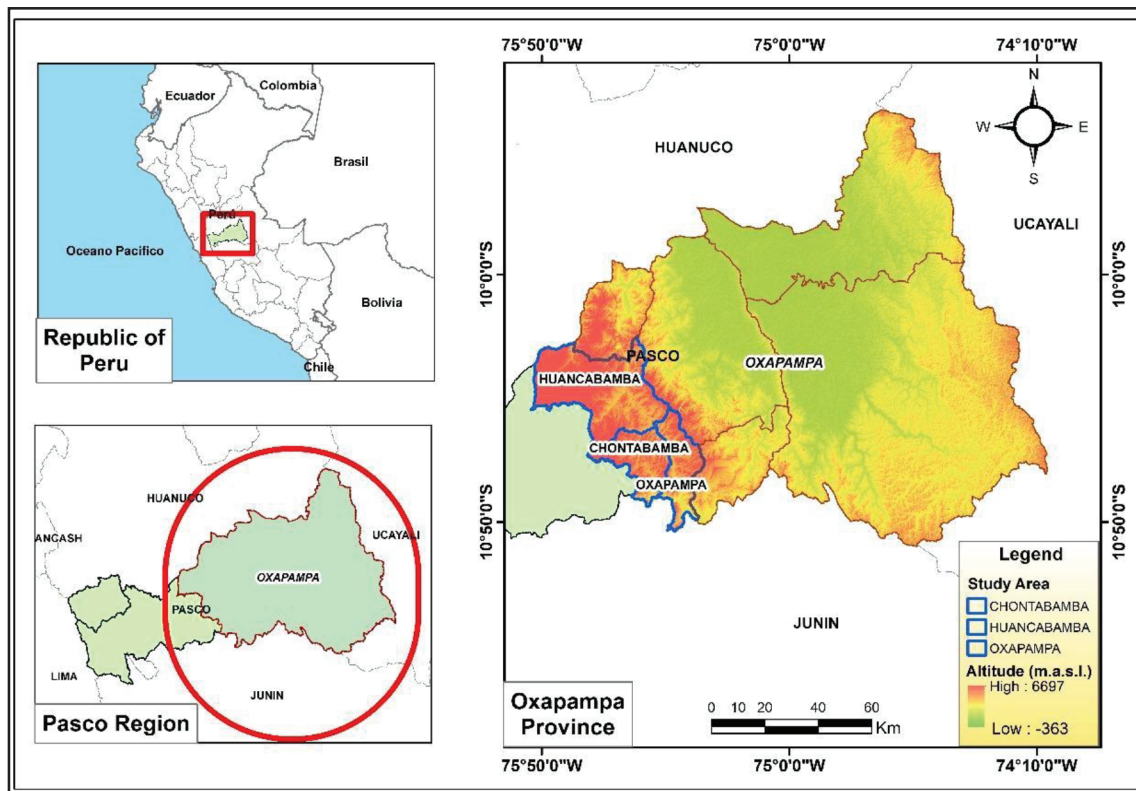


Fig. 1. Geographic location of the study area (ArcGIS 10.8 was used to generate the map).

n: sample size, N : population size, Z : value in the normal distribution table (1.96), p : expected probability, (0.5) q : probability of failure (0.5), E = Margin of error (3.5%). The estimated sample consisted of 210 cattle producers, who were surveyed and distributed across the following districts: Oxapampa (76), Chontabamba (40), and Huancabamba (94). The sampling frame was developed based on the most recent official database from the National Institute of Statistics and Informatics (2012), which recorded 284 producers in the region. This information was used as a reference for calculating the sample size, given that the Pasco department has no updated census of livestock producers. This database also allowed producers to be stratified according to their district, ensuring a balanced representation of the territory. Although the time gap could generate some discrepancy with respect to the current population size, direct field verification and consultation with complementary sources, such as the non-governmental organization INTERSOCIAL SAC (2017), which operates in the area, reduced this limitation. These sources confirmed that the spatial distribution of producers remains stable and that the average annual increase in the cattle population is 2.2%. The sample used in this study (210 producers) represents approximately 56% of the estimated population of cattle producers in the three districts

evaluated in the province of Oxapampa. Thus, the approach allowed us to obtain reliable and relevant results for the multivariate analysis.

Variable selection

Data collection was performed using a structured survey organized into five components: social, farm management, pasture management, animal production, and economic-financial. The survey comprised 78 categorical and numerical variables. A total of 210 farms were visited. Before data collection, producers were informed that the survey was being conducted for research, and their informed consent was obtained before they responded to the questionnaire. Surveys were conducted at each producer's farm to verify the accuracy of their responses. In addition, care was taken to ensure that the responses provided were as reliable as possible. The evaluation of these variables was conducted through an exhaustive analysis of documentation, structured surveys, and field observation using registration forms and questionnaires. IBM SPSS Statistics 27 software was used for data analysis, employing two scaling options: the PROXSCAL multidimensional scaling method and optimal scaling with nominal and scalar variables (IBM Corp, 2020). The PROXSCAL method was applied to the 78 variables, yielding a spatial representation with a normalized raw stress value of 0.03589, indicating an excellent model fit. Based on the largest Euclidean

distances among the variables, 24 variables were selected (Table 1). These 24 variables were then used in the CATPCA, which facilitated the identification of significant patterns within the evaluated cattle production systems.

Categorical principal component analysis

The CATPCA was performed by optimal scaling using IBM SPSS Statistics 27 software. The algorithm employs an alternating least squares method (ALS) that iteratively assigns numerical quantifications to the categories of each variable, subject to the constraints of their measurement levels (nominal, ordinal, or numerical), to maximize the variance accounted for by a low-dimensional solution (Kuroda et al., 2013). Following convergence, a singular value decomposition of the optimally scaled data matrix produced the principal components and their associated loadings (Linting and van der Kooij, 2012). Twenty-three categorical variables and one numerical variable were included in the analysis, resulting in a variance and loading matrix for 10 dimensions. For nominal variables with more than two categories (13 variables, representing 54% of the categorical variables), the “Multiple Nominal” scaling option (centroid quantification) was selected. Unlike “Single Nominal” scaling, this approach does not produce a single loading vector for the variable as a whole. Consequently, these variables were excluded from the standard correlation calculation (loadings). Instead, their contribution to the extracted dimensions was evaluated from the variance matrix, and the magnitude of their influence was estimated based on the square root of the variance associated with each dimension. This allowed the calculation of the magnitude but not the sign or direction of the loadings.

The scale’s reliability was assessed using Cronbach’s alpha coefficient, which guaranteed the internal consistency of the components obtained. The communalities (h^2) were estimated in a differentiated manner: for ordinal and binary variables, it was calculated as the sum of the variances, whereas for nominal variables, the average of the variances was used. This procedure allowed the assessment of the representativeness of each variable within the model, ensuring an adequate interpretation.

The main objective of CATPCA was to reduce the dimensionality of the data space, simplify the analysis, and provide specific descriptions of the system under study. Following the methodologies proposed by Peña (2002) and Jobson (2012), this approach is an effective tool for identifying key patterns and optimizing the interpretation of categorical data in production systems. Unlike previous studies that relied primarily on numerical variables, this study incorporates categorical information to better capture differences in production typologies within the high tropical context, integrating both the technological and socioeconomic dimensions of livestock farming. The application of

this method represents a significant contribution to the characterization and improvement of complex production systems. Finally, a three-dimensional (3D) plot was generated to visualize the distribution of producers along the first three principal components, grouped by district.

Hierarchical cluster analysis

HCA was performed using the scores obtained from the first 10 dimensions of the CATPCA, representing 210 cattle producers. Before clustering, the data were standardized. We employed the Euclidean distance and Ward’s minimum variance method because this combination is known to perform well with continuous data and tends to produce compact, spherical clusters. The analysis was conducted in RStudio using *tidyverse*, *cluster*, *factoextra*, and *NbClust* packages (R Core Team, 2023). The optimal number of clusters was determined using two complementary criteria: (i) the average silhouette width and (ii) the total within-cluster sum of squares based on the elbow method. Three clusters were identified: Traditional Extensive System (TES), Improved Dual-Purpose Extensive System (IDPES), and Semi-Intensive System (SIS).

Statistical analysis

To characterize the identified clusters, the Kruskal–Wallis non-parametric test was employed for ordinal and numeric variables, with effect sizes estimated using the eta-squared statistic and post hoc pairwise comparisons conducted through Dunn’s test with Holm adjustment. Fisher’s exact test was applied for nominal and binary categorical variables, with effect sizes determined by Cramer’s V coefficient and subsequent post hoc analyses also performed using Fisher’s test. This analytical approach enabled a comprehensive characterization of the clusters’ structural and operational differences, providing robust evidence for the factors that differentiate each production system.

Ethical approval

Not needed for this study.

Results

Categorical principal component analysis (CATPCA) was performed

Table 2 shows that the variables related to milk production (0.42), cattle dosing (0.41), and cow culling age (0.40) present moderate communalities compared to the remaining variables, indicating that the retained principal components explain more than 40% of the variability of these variables. This suggests that they play a key role in differentiating cattle production systems. The cumulative variance explained by the CATPCA was 22.46%, which can be considered relatively low but similar to other studies (Wairimu et al., 2021). Table 2 details the percentage of explained variance and communality values for each principal component, where higher values denote stronger explanatory power within the model. Figure 2 illustrates

Table 1. Components and variables considered in the typology analysis.

Components	Variable	Type	Categories
Social	Household composition	Numeric	1, 2, 3, 4, and 5 people.
	Age of the head of household	Ordinal	20–30, 31–40, 41–50, 51–60, 61–70 years.
	Educational level of the household head	Ordinal	Incomplete or complete primary and secondary education or higher education.
Property management	The pasture area on the farm	Ordinal	1–20, 21–40, 41–60, > 60 ha.
	Land use	Nominal	Agricultural, agricultural and pastures, agricultural and pastures and forestry and other uses, agricultural and pastures and forestry, pastures, pastures and forestry.
	Agricultural crops	Binary	Cultivated, non-cultivated
Pasture management	Period of pasture establishment	Nominal	January–February, March–April, May–June, July–August, September–October, November–December.
	Age of the cultivated pastures	Ordinal	0–5, 6–10, 11–20, 21–30, 31–40 years.
	Primary pasture species	Nominal	African star, brachiaria, dordura (<i>Melinis minutiflora</i>), grass, kikuyu, native, pangola, setaria (<i>Setaria sphacelata</i>), and other pastures.
	Pasture storage	Binary	Stores and non-stores.
	Primary pasture pests	Nominal	Ants, crickets, diabrotic, grasshopper, slug, spittlebug, and none.
	Pasture fumigation	Binary	Fumigate, non-fumigate.
Animal production	Milk production herd/day	Ordinal	0, 10–15, 16–25, 26–35, 36–50, 60–80, 140–150 liters.
	Cow Culling Age	Ordinal	Non sale, <2, 2–4, 4–6, >6 years.
	Type of cattle feed used	Nominal	Cultivated and natural pasture, cultivated pasture and crop residues, cultivated pasture and crop residues and other feed resources, and natural pasture.
	Origin of bull breeding	Nominal	Codo del Pozuzo, Huancayo, Lima, Oxapampa, Palcazu, Pozuzo, and Puno
	Method of cattle curing	Nominal	Only family, only veterinary, family, and veterinary.
Animal production	Cattle dosing	Binary	Dose, no dose
	Causes of calf mortality	Nominal	Carbuncle, neglect, parasites, piroplasmosis, pneumonia, tympany, white diarrhea
	Rearing of the older animals	Nominal	Only cattle, cattle and pigs, cattle and sheep, and cattle and pigs and sheep.
	Limitations in cattle is rearing	Nominal	Genetic factors, inadequate technology, limited capital, land scarcity, and non-limitations.
Economic–Financial	Source of household income	Nominal	Sale of agricultural products, livestock, cheese, milk, and other items.
	Milk production destination	Nominal	Cheesemakers, dairy plants, milk collectors, direct sales to the public, and self-consumption.
	Allocation of Financial Loans	Nominal	Improvement of animal genetics, property, infrastructure expansion, land acquisition, and pasture.

the distribution of producers across the first three principal components, grouped by district. A marked dispersion is observed in the Oxapampa district, reflecting greater variability among producers, whereas

the distributions in Chontabamba and Huancabamba are more homogeneous.

Principal Component 1 (DI), which accounts for 10.915% of the total variance, reveals the influence

Table 2. Loadings matrix from categorical principal component analysis (CATPCA).

Variable	Dimensions										Communality
	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	(h ²)
Household composition	-0.071	0.248	-0.046	0.211	0.279	-0.208	0.055	-0.099	-0.178	0.020	0.279
Age of the head of household	-0.336	0.193	-0.200	0.045	-0.194	-0.097	-0.194	-0.041	0.207	0.062	0.325
Educational level of the household head	-0.364	-0.179	-0.208	0.081	-0.027	-0.237	0.321	0.060	0.119	0.005	0.392
The pasture area on the farm	0.236	-0.012	-0.153	-0.092	-0.115	-0.111	0.176	0.186	0.269	-0.111	0.263
Age of the cultivated pastures	-0.326	0.156	-0.010	-0.183	-0.130	0.302	0.200	0.021	-0.072	0.269	0.390
Milk production	0.405	0.015	0.448	-0.030	-0.034	-0.027	-0.204	-0.074	-0.037	-0.038	0.418
Cow Culling Age	0.411	-0.194	0.279	-0.049	0.206	0.093	0.136	-0.187	-0.029	0.058	0.396
Land use (*)	0.369	0.311	0.436	0.448	0.274	0.173	0.355	0.417	0.311	0.474	0.135
Rearing of older animals (*)	0.471	0.555	0.195	0.141	0.243	0.336	0.089	0.214	0.230	0.263	0.094
Period of pasture establishment (*)	0.219	0.375	0.356	0.424	0.232	0.424	0.378	0.277	0.401	0.377	0.125
Main pasture pests (*)	0.512	0.375	0.313	0.445	0.279	0.454	0.571	0.322	0.412	0.182	0.162
Main pasture species (*)	0.344	0.414	0.522	0.487	0.498	0.520	0.315	0.534	0.300	0.473	0.201
Type of cattle feed (*)	0.126	0.367	0.241	0.276	0.329	0.176	0.535	0.266	0.105	0.559	0.110
Method of cattle curing (*)	0.105	0.110	0.170	0.329	0.367	0.342	0.212	0.179	0.464	0.134	0.072
Causes of calf mortality	0.253	0.509	0.349	0.344	0.499	0.468	0.322	0.437	0.392	0.342	0.160
Origin of the breeding bulls (*)	0.349	0.511	0.482	0.414	0.444	0.494	0.243	0.416	0.330	0.395	0.172
Household income source (*)	0.590	0.496	0.192	0.197	0.529	0.371	0.190	0.352	0.349	0.483	0.160
Milk production destination (*)	0.322	0.158	0.504	0.445	0.407	0.298	0.277	0.373	0.315	0.352	0.128

Continued

Table 2. Loadings matrix from categorical principal component analysis (CATPCA).

Limitations in cattle rearing (*)	0.333	0.440	0.138	0.436	0.197	0.272	0.345	0.383	0.288	0.170	0.101
Financial loan allocation (*)	0.349	0.440	0.502	0.263	0.415	0.313	0.322	0.276	0.484	0.084	0.133
Agricultural crops	-0.192	-0.080	0.192	0.208	-0.045	-0.062	-0.166	-0.188	-0.188	0.144	0.248
Pasture fumigation	0.376	0.101	-0.049	-0.185	-0.069	-0.013	-0.199	-0.172	0.010	0.035	0.264
Pasture storage	0.080	0.145	0.022	-0.169	-0.165	0.130	0.338	-0.102	0.177	0.014	0.257
Cattle dosing	0.083	-0.011	-0.343	0.360	-0.078	-0.066	-0.057	0.360	-0.043	0.077	0.405
Eigenvalues	2.620	2.415	2.271	2.137	2.091	2.058	1.990	1.936	1.835	1.811	5.390
Cumulative Variance	10.915	10.062	9.464	8.902	8.712	8.574	8.292	8.068	7.645	7.545	22.46 %

(*) Estimated loadings based on variance matrix

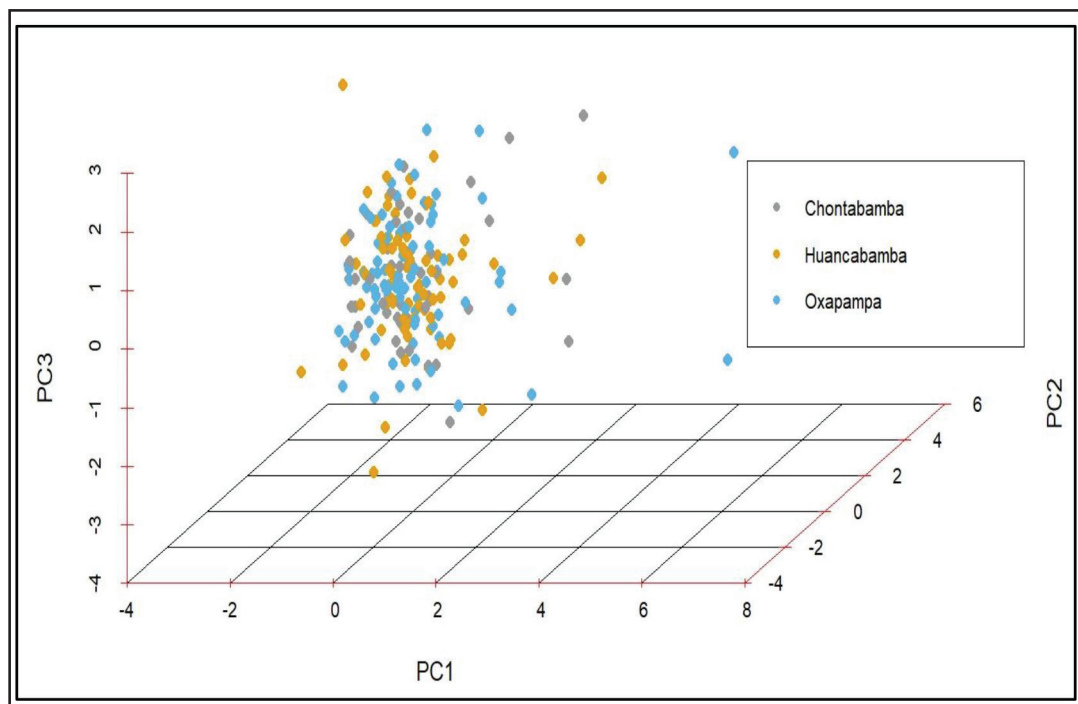


Fig. 2. Three-dimensional representation of the first 3 components of the CATPCA for cattle producers according to the district of origin PC: component..

of variables with moderate communalities, such as household income source (0.59), main pasture pests (0.51), rearing of older animals (0.47), cow culling age (0.41), and milk production (0.41). This component reflects the interaction between socioeconomic and management factors that shape cattle production systems' sustainability and profitability. Similar

findings have been reported in other studies (Cuevas-Reyes *et al.*, 2018).

Principal Component 2 (D2) explains 10.062% of the total variance and reveals relationships among variables with moderate communalities, such as the origin of breeding bulls (0.51), causes of calf mortality (0.51), limitations in cattle rearing (0.44), allocation

of financial loans for livestock activities (0.44), and main pasture species (0.41). This component reflects the interaction of ecological, genetic, health, and economic factors that shape cattle production systems' sustainability, profitability, and efficiency.

Principal Component 3 (D3) accounts for 9.464% of the total variance and reveals the relationship among variables with moderate communalities, such as milk production destination (0.50) and land use (0.44). This component reflects the interaction between economic and territorial management factors that determine cattle production systems' sustainability and efficiency. Producers who primarily market their milk to dairy plants tend to allocate more land to more intensive and specialized systems, investing more in improved pastures and supplementary feeding, thereby enhancing technical efficiency. Producers who allocate part of their milk production for household consumption or local markets often maintain a more diversified land-use pattern, incorporating agricultural and forestry activities.

Dimensions D4, D7, and D9 capture specific aspects of management practices related to pasture establishment period (0.42), cattle feed type (0.54), and cattle curing method (0.46), respectively. The observed moderate correlations suggest that these factors partially contribute to the overall structure of production systems, although they are not dominant sources of variability. Conversely, the low correlations observed in the remaining dimensions indicate that most variables exhibit weak associations with the extracted latent

dimensions, which may reflect the high heterogeneity among producers or context-dependent management decisions.

Characterization of cattle production systems

The HCA identified three distinct clusters (Fig. 3): the TES, represented by 17 producers; the SIS, comprising 64 producers; and the IDPES, comprising 129 producers.

Table 3 presents comparisons among clusters for social components. Household composition ($P = 0.749$) and age of the household head ($P = 0.489$) were similar across clusters, whereas the educational level of the household head ($P = 0.003$) was significantly different. However, all 3 variables exhibited small effect sizes, indicating that these social factors only marginally contribute to the differentiation among groups.

All producers had 3 family members on average, and the household head was between 41 and 60 years old, suggesting substantial experience in farm management. The main difference among clusters was observed in the educational level: most producers in the TES cluster had completed only primary education, whereas those in the SIS and IDPES clusters had completed secondary education.

Table 4 presents comparisons among clusters for farm management components. The results indicate that the clusters did not differ significantly in terms of pasture area ($P = 0.634$); farms typically have between 1 and 20 hectares designated for pasture. In contrast, significant differences were observed for land use ($P = 0.001$) and agricultural crops ($P = 0.025$), suggesting that these

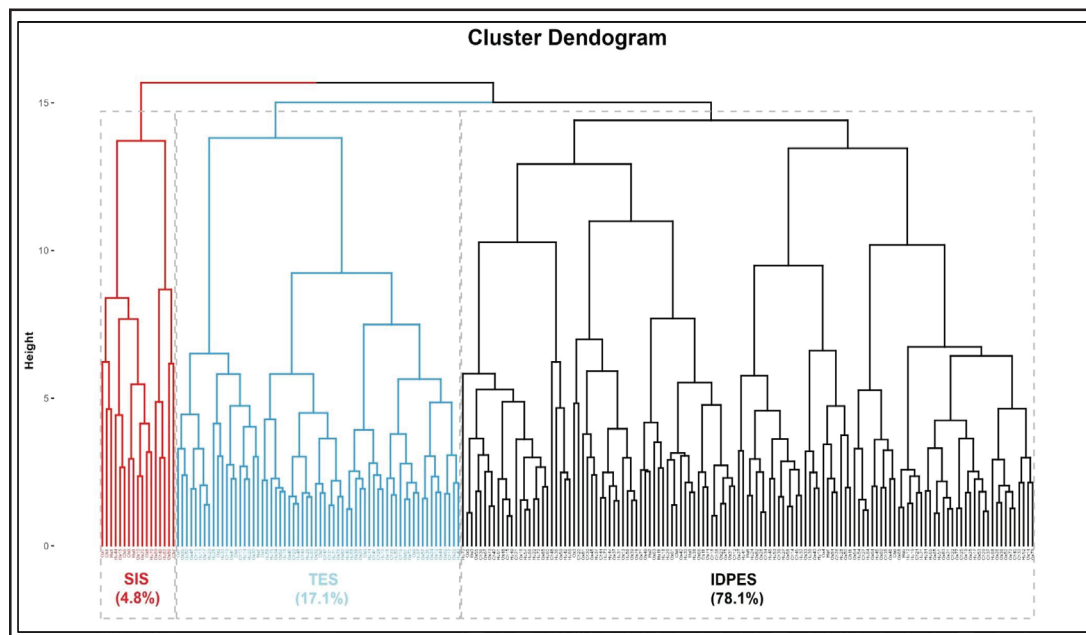


Fig. 3. Dendrogram of the three cattle production systems TES: Traditional Extensive System; SIS: Semi-Intensive System; IDPES: Improved Dual-Purpose Extensive System

Table 3. Comparison of the social components of cattle production systems.

Variable	TES	SIS	IDPES	p-value	Size effect
Household composition (m)	3 ^a	3 ^a	3 ^a	0.749	−0.007 [small]
Age of the head of household	41–50 years (29.4%) ^a	51–60 years (25.0%) ^a	41–50 years (34.9%) ^a	0.489	−0.003 [small]
Educational level of the household head	Completed primary school (58.8%) ^a	Completed secondary (42.2%) ^b	Primary and secondary (40.3% each) ^b	0.003**	0.0453 (small)

TES: Traditional Extensive System; SIS: Semi-Intensive System; IDPES: Improved Dual-Purpose Extensive System; (m) median; (**) p -value < 0.01; Value in parentheses is the major frequency within the cluster; Value in brackets is the interpretation of the size effect. Frequencies with different superscripts (a,b,c) within a row differ significantly (p < 0.05).

Table 4. Comparison of the farm management components of cattle production systems.

Variable	TES	SIS	IDPES	p-value	Size effect
The pasture area on the farm	1–20 ha (52.9%) ^a	1–20 ha (67.2%) ^a	1–20 ha (63.6%) ^a	0.634	−0.005 [small]
Land use	Pastures (35.3%) ^{a,b}	Agricultural and pastures (40.6%) ^a	Agriculture, pastures, and forestry (32.6%) ^b	0.001 **	0.247 [moderate]
Agricultural crops	Cultivates (58.8%) ^b	Cultivates (68.8%) ^{a,b}	Cultivates (82.2%) ^a	0.025 *	0.187 [small]

TES: Traditional Extensive System; SIS: Semi-Intensive System; IDPES: Improved Dual-Purpose Extensive System; (*) p -value < 0.05, (**) p -value < 0.01; Value in parentheses is the major frequency within the cluster; Value in brackets is the interpretation of the size effect. Frequencies with different superscripts (a,b,c) within a row differ significantly (p < 0.05).

factors contribute to cluster differentiation. However, only land use showed a moderate effect size, while the other variables exhibited small effects, indicating that land use plays a noticeable, though not predominant, role in differentiating farm management strategies across clusters.

The SIS system primarily allocates land to agricultural crops and pastures, promoting diversification and reducing dependence on a single production source. The IDPES system integrates agricultural crops, pastures, and forestry activities within the same production unit, suggesting higher resource optimization and multifunctionality. In contrast, the TES system almost exclusively uses its land for pasture cultivation, reflecting limited diversification and lower technological adoption.

Table 5 presents the comparisons among the clusters of pasture management components. The results indicate that the clusters did not differ significantly in terms of pasture establishment ($P = 0.273$) and pasture storage ($P = 0.079$). Farms typically establish pastures between January and February and do not store forage, which makes them vulnerable during droughts or other dry periods. This seasonal dependence on natural or cultivated pasture growth exposes cattle herds to feed

shortages, resulting in reduced milk production and weight loss.

In contrast, significant differences were observed for the age of cultivated pastures ($P = 0.004$), main pasture species ($P = 9.9\text{e-}05$), pests ($P = 4.9\text{e-}04$), and pasture fumigation ($P = 3.3\text{e-}04$), indicating that these variables contribute to cluster differentiation. The main pasture species and pest variables showed large effect sizes, demonstrating that they play a decisive role in distinguishing cattle production clusters. Although pasture fumigation exhibited a moderate effect size, it exerted a less dominant influence than the other two variables, whereas the remaining factors, which showed small effect sizes, only marginally contributed to the differentiation among systems.

The SIS system is characterized by the predominance of *Setaria sphacelata* pastures older than 30 years, suggesting a stable but potentially degraded forage base. In this system, 97% of producers perform fumigation on their farms and report few pest problems. In the IDPES system, pastures of *S. sphacelata* are younger (11–20 years), reflecting more active renovation and better management practices, supported by higher education levels and greater investment capacity. In this system, 88% of producers perform fumigation, largely keeping pest levels under control. Conversely,

Table 5. Comparison of the pasture management components among cattle production systems.

Variable	TES	SIS	IDPES	p-value	Size effect
Period of pasture establishment	January–February (52.9%) ^a	January–February (42.2%) ^a	January–February (41.1%) ^a	0.273	0.175 [small]
Age of the cultivated pastures	6–10 years (29.4%) ^b	31–40 years (32.8%) ^a	11–20 years (32.6%) ^b	0.004 **	0.0432 [small]
Primary pasture species	<i>Melinis minutiflora</i> (29.4%) ^c	<i>Setaria sphacelata</i> (40.6%) ^a	<i>Setaria sphacelata</i> (31.8%) ^b	9.9e–05 ***	0.359 [large]
Pasture storage	Nonstore (76.5%) ^a	Nonstore (78.1%) ^a	Nonstore (62.8%) ^a	0.079	0.157 [small]
Primary pasture pests	Slug and none (35.3% each) ^b	None (48.4%) ^a	None (51.2%) ^a	4.9e–04 ***	0.360 [large]
Pasture fumigation	Fumigate (58.8%) ^c	Fumigate (96.9%) ^a	Fumigate (87.6%) ^b	3.3e–04 ***	0.298 [moderate]

TES: Traditional Extensive System; SIS: Semi-Intensive System; IDPES: Improved Dual-Purpose Extensive System; ** p -value < 0.01; *** p -value < 0.001; Value in parentheses is the major frequency within the cluster; Value in brackets is the size effect interpretation. Frequencies with different superscripts (a,b,c) within a row differ significantly ($p < 0.05$).

the TES system presents younger pastures (6–10 years old) dominated by *Melinis minutiflora* (gordura grass), a species that thrives in low-fertility soils and less intensively managed environments. Approximately 59% of TES producers use pesticides to control slug infestations that cause severe defoliation and reduce pasture vigor and productivity.

Table 6 presents the comparisons among clusters for the components of animal production. The clusters did not differ significantly in terms of milk production ($P = 0.107$), cattle dosing ($P = 0.368$), and cattle rearing limitations ($P = 0.075$). Although the proportion of milk-producing farms is similar across clusters, production levels vary, with the SIS system showing the highest yields (140–150 liters) and the TES system the lowest (36–50 liters). All systems administer antiparasitic treatments to their cattle but face structural constraints in herd expansion due to land scarcity and limited capital availability.

In contrast, significant differences were observed for the type of cattle feed ($P = 0.010$), cow culling age ($P = 2.9e-04$), method of cattle curing ($P = 1.5e-04$), origin of breeding bulls ($P = 9.9e-05$), causes of calf mortality ($P = 9.9e-05$), and rearing of older animals ($P = 6.9e-06$). The origin of breeding bulls, causes of calf mortality, and rearing of older animals exhibited large effect sizes, suggesting that these variables play a decisive role in differentiating cattle production systems. More than 50% of producers in the SIS and IDPES systems use improved regional bulls that have been adapted to local climatic conditions. In contrast, more than 40% of producers in the TES system rely on foreign genetics, which require a period of adaptation and sometimes result in animal losses.

Cow culling age and cattle culling method showed moderate effect sizes, indicating an intermediate

influence on cluster differentiation. Producers in the IDPES and SIS systems primarily sell cows between 2 and 4 years of age (62% and 43%, respectively), whereas those in the TES system tend to keep cows longer, often beyond 6 years of age. Regarding animal health, more than 50% of producers in the IDPES and TES systems administer treatments themselves, whereas 42% of SIS producers seek veterinary assistance. Finally, the species composition within farms differed among the systems. In the SIS and IDPES systems, 93% and 87% of producers raised only cattle, respectively, indicating higher specialization. In contrast, only 47% of TES producers solely raised cattle, with the remainder maintaining mixed herds of cattle and pigs.

Table 7 presents comparisons among clusters for economic-financial components. The clusters differed significantly in terms of household income source ($P = 9.9e-05$), destination of milk production ($P = 2.9e-04$), and allocation of financial loans ($P = 9.9e-05$). These differences suggest that each cluster has a distinct socioeconomic and productive profile. The 3 variables exhibit effect sizes ranging from moderate to large, suggesting that they are key factors in differentiating cattle production systems.

In the IDPES system, 54% of producers rely primarily on livestock farming as their main source of income, which may limit economic diversification and increase vulnerability to market and climatic fluctuations. In contrast, 34% of producers in the SIS system primarily derive their income from crop production and the sale of animal products, whereas 29% of producers in the TES system mainly depend on livestock sales and miscellaneous goods. Regarding milk destination, producers in the TES system mainly allocate milk for self-consumption, whereas those in the SIS and IDPES systems direct their production toward dairy plants

Table 6. Comparison of the animal production components among cattle production systems.

Variable	TES	SIS	IDPES	p-value	Size effect
Milk production	36–50 L (29.4%) ^a	140–150 L (26.6%) ^a	60–80 L (28.7%) ^a	0.107	0.012 [small]
Cow Culling Age	2–4 years, and nonsale (35.3% each) ^b	2–4 years (43.8%) ^b	2–4 years (62.8%) ^a	2.9e–04 ***	0.069 [moderate]
Type of cattle feed used	Cultivated pasture, crop residue, and others (47.1%) ^{a,b}	Cultivated pasture, crop residue, and others (50.0%) ^a	Cultivated pasture and crop residue (40.3%) ^b	0.010 *	0.189 [small]
Origin of bull breeding	Lima (41.2%) ^c	Oxapampa (51.6%) ^b	Oxapampa (59.7%) ^a	9.9e–05 ***	0.358 [large]
Method of cattle curing	Only family (47.1%) ^{a,b}	Veterinarian only (42.2%) ^b	Only family (58.9%) ^a	1.5e–04 ***	0.236 [moderate]
Cattle dosing	Dose (94.1%) ^a	Dose (98.4%) ^a	Dose (93.8%) ^a	0.368	0.100 [small]
Causes of calf mortality	Neglect (29.4%) ^a	Pneumonia (23.4%) ^b	Pneumonia (24.0%) ^a	9.9e–05 ***	0.360 [large]
Rearing of the older animals	Only cattle (47.1%) ^c	Only cattle (93.8%) ^a	Only cattle (87.6%) ^b	6.9e–06 ***	0.374 [large]
Limitations in cattle rearing	Limited capital (47.1%) ^a	Land scarcity (46.9%) ^a	Land scarcity (41.1%) ^a	0.075	0.170 [small]

TES: Traditional Extensive System; SIS: Semi-Intensive System; IDPES: Improved Dual-Purpose Extensive System; **p*-value < 0.05; ****p*-value < 0.001; Values in parentheses indicate the major frequency within the cluster; Values in brackets indicate the size effect. Frequencies with different superscripts (a,b,c) within a row differ significantly (*p* < 0.05).

Table 7. Comparison of the economic-financial component among cattle production systems

Variable	TES	SIS	IDPES	p-value	Size effect
Source of household income	Sale of animals and other items (29.4% each) ^c	Sale of agricultural products (34.4%) ^b	Sale of livestock (54.3%) ^a	9.9e–05 ***	0.351 [large]
Milk production destination	Self-consumption (35.3%) ^b	Dairy plants (71.9%) ^a	Dairy plants (44.2%) ^b	2.9e–04 ***	0.250 [moderate]
Allocation of Financial Loans	Property improvement (41.2%) ^b	Genetic improvement (48.5%) ^a	Pasture improvement (28.7%) ^b	9.9e–05 ***	0.285 [moderate]

TES: Traditional Extensive System; SIS: Semi-Intensive System; IDPES: Improved Dual-Purpose Extensive System; (***) *p*-value < 0.001; Value in parentheses is the major frequency within the cluster; Value in brackets is the interpretation of the size effect. Frequencies with different superscripts (a,b,c) within a row differ significantly (*p* < 0.05).

and formal markets, which typically demand higher quality standards but provide more stable income opportunities. Differences in the allocation of financial loans were also observed. Producers in the SIS system primarily invest in animal genetic improvement, whereas those in the TES and IDPES systems focus on enhancing farm infrastructure and pasture quality.

Discussion

Categorical principal component analysis (CATPCA) is performed

The relatively low cumulative variance (22.46%) arises because it does not correspond to the direct sum of the variances of the dimensions due to

the inclusion of nominal variables with multiple categories (IBM Corp., 2020), which accounted for 54% of the evaluated variables. However, this level of explained variance is typical in multivariate analyses that include numerous categorical variables (Wairimu *et al.*, 2021; Rodríguez-Vargas *et al.*, 2025), where a significant portion of variability reflects the heterogeneity of production contexts rather than shared structural patterns. Although the explained variance may represent a limitation of the model, the retained dimensions effectively synthesize the most relevant patterns and provide a robust basis for the subsequent classification of cattle production systems.

Cuevas-Reyes and Rosales-Nieto (2018) highlighted the critical role of pasture management, socioeconomic conditions, and livestock productivity in determining the efficiency and sustainability of production systems. Likewise, Marizancén and Artunduaga (2017) emphasized that income diversification and efficient financial resource management are key determinants of livestock farm profitability. In our study, producers with diversified income sources – such as the sale of live animals, agricultural products, and milk – as well as complementary livestock activities, such as cattle and pig farming, tended to exhibit greater economic stability and more sustainable resource management. In addition, the adoption of integrated pest and slug management practices helps preserve pasture productivity, thereby improving feed efficiency and milk yield. Proper planning of cow culling age also contributes to optimizing productive performance and reducing costs associated with maintaining unproductive animals, thus strengthening the system's overall economic sustainability.

The selection of well-adapted forage species, such as *S. sphacelata*, together with efforts to reduce calf mortality through training and outreach activities focused on calf care, health, and disease prevention, strengthens the biological foundation of production systems. Verdon (2022) noted that reducing calf mortality in grazing systems can be achieved through improvements in animal health and welfare, with the associated costs offset by productivity gains due to higher calf survival rates. Moreover, the origin and local genetic quality of breeding bulls adapted to high tropical conditions influence both herd productivity and resilience. Similarly, Escobar *et al.* (2024) emphasized that the origin of breeding bulls and forage quality are key factors in enhancing genetic improvement and overall herd performance. Identifying structural limitations and strategically allocating credit resources to improve feeding practices, genetic quality, infrastructure, and animal management contribute to strengthening economic sustainability, profitability, and productive efficiency. Galina and Geffroy (2023) also reported that tropical cattle production systems are often constrained by inadequate record-keeping, limited investment capacity, the absence of breeding programs, harsh environmental conditions, poor infrastructure, and suboptimal nutritional and health management, all of which collectively reduce productivity.

The results indicate that milk destination and land-use patterns are closely linked to production strategies and system sustainability. Producers who supply milk to dairy plants generally operate more specialized and intensive systems, prioritizing improved pastures and supplemental feeding to maximize productivity and efficiency. Sturaro *et al.* (2013) reported similar findings, noting that farms delivering milk to cheese factories tend to expand pasture areas and adopt more intensive management practices. Producers who retain

part of their milk for self-consumption or local sales maintain diversified land uses, integrating agricultural and forestry activities. Diversification enhances the environmental and social sustainability of production systems by balancing economic objectives with food security and resource conservation. Fierro *et al.* (2020) emphasized that the production destination (dairy industry vs. self-consumption) and land-use patterns (agricultural or mixed systems) are key factors contributing to the heterogeneity of cattle production systems in tropical regions and should be considered when characterizing such systems.

Characterization of cattle production systems

In relation to the social component (Table 3), the finding that household heads are generally between 41 and 60 years old aligns with Barrantes *et al.* (2021), who reported that farmers in this age range tend to have extensive experience in livestock management, a deep understanding of local natural resources, and greater capacity for strategic planning to face adverse events. Educational level differences among clusters appear to play a more significant role in shaping management capacity and innovation adoption. Leos-Rodríguez *et al.* (2008) found that families with lower education levels can improve productive performance when they participate in technical training-based extension programs. Similarly, Rodríguez-Vargas *et al.* (2022) observed that producers in Oxapampa with lower performance often make limited use of technology, particularly within traditional systems. Producers in the SIS system – characterized by household heads over 50 years old with higher educational attainment – possess a clear competitive advantage in this context. Their greater access to education enhances their ability and willingness to adopt innovations such as improved animal and pasture management practices, efficient use of reproductive and health technologies, and better record-keeping for production and economic monitoring (Torres *et al.*, 2015; Abebe *et al.*, 2025).

As for the farm management component (Table 4), the results highlight that land use is a key factor distinguishing cattle production systems, underscoring the importance of monitoring and guiding land-use changes toward scenarios that enhance resilience and productivity. As suggested by Rivera *et al.* (2024), promoting silvopastoral systems can improve farm sustainability and reduce GHG emissions. Achieving this transition requires the incorporation of remote sensing and precision livestock technologies – such as drones – that allow for more efficient land and pasture management, representing a forward-looking step in the modernization of tropical cattle production systems. The SIS system's diversified land allocation between crops and pastures enhances sustainability by improving nutrient cycling, soil structure, and forage availability throughout the year – factors crucial for resilience in tropical environments (Sharma *et al.*, 2025). Similarly, the integration of crops, pastures, and

forestry in the IDPES system aligns with agroforestry principles, promoting economic stability and environmental conservation. The coexistence of these strategies demonstrates the heterogeneity and adaptive capacity of cattle production systems in the Peruvian tropics, where resource availability, market conditions, and household objectives shape land management decisions (Bui and Nguyen, 2022). Conversely, the TES system's exclusive focus on pasture cultivation, with limited crop integration, increases vulnerability to seasonal forage shortages and land degradation – patterns commonly observed in low-input cattle systems (Van-Heurck *et al.*, 2020). This limited diversification limits the potential for technological adoption and long-term sustainability in such production contexts. Focusing on the pasture management component (Table 5), the limited use of pasture conservation practices, such as silage or haymaking, underscores the vulnerability of these systems to seasonal feed shortages and highlights the low adoption of feed management technologies typical of smallholder livestock systems in the Peruvian tropics (Tongo and Soplin, 2022). The significant differences observed in pasture age, dominant species, and pest management across clusters reflect contrasting land-use histories, management intensities, and investment capacities. The persistence of long-established *S. sphacelata* pastures in the SIS system suggests a stable production base but also a potential productivity decline due to aging stands and reduced regeneration. This likely explains the widespread use of fumigation (97%) as a pest control measure. Similarly, the IDPES system shows a proactive approach to pasture renovation and pest management, supported by better access to technical knowledge and financial resources, enabling sustainable pasture maintenance. In contrast, the TES system, dominated by *M. minutiflora*, represents a more opportunistic strategy suited to low-input conditions. While this species offers rapid establishment and tolerance to poor soils, it is also highly susceptible to slug damage, which severely limits forage biomass and productivity. As noted by Ferguson *et al.* (2019), such challenges lead to reduced stocking rates and lower milk and meat outputs. These patterns underscore the need to strengthen pasture renewal, pest control, and conservation practices to enhance the resilience and productivity of traditional cattle systems. The lack of significant differences in milk production among clusters suggests that productivity constraints are systemic rather than cluster-specific (Table 6). However, differences in yield levels indicate varying degrees of technological adoption, pasture management efficiency, and access to inputs and veterinary services. Higher milk yields in the SIS system likely reflect better pasture quality, improved breeds adapted to local conditions, and more structured management practices, whereas low yields in the TES system may stem from limited access to resources and poor pasture quality. All systems

share similar limitations in herd expansion due to land and capital scarcity – common structural barriers in tropical smallholder systems (Banda and Tanganyika, 2021). These conditions constrain reinvestment and perpetuate low productivity and economic vulnerability. Policy interventions aimed at improving access to credit, technical assistance, and sustainable intensification strategies are essential for breaking this cycle. Significant differences in feeding practices, bull breeding origin, calf mortality, and rearing of older animals highlight the role of management and genetic strategies in shaping system performance. The use of locally adapted bulls in the SIS and IDPES systems aligns with the findings of Barendse (2017) and Escobar *et al.* (2024), who emphasize the importance of genetic adaptation and selection based on local environmental conditions to enhance herd productivity and resilience. Biosecurity measures must also be strengthened, particularly in the SIS and IDPES systems, to reduce calf mortality from infectious diseases such as pneumonia, carbuncle, and white diarrhea. Effective extension and outreach programs promoting best practices in calf rearing could substantially improve survival rates and overall system productivity (Verdon, 2022). Livestock diversification patterns further differentiate production systems. The predominance of specialized cattle farming in the SIS and IDPES systems may support higher productivity but limits economic diversification and resilience. In contrast, the mixed-species approach (cattle and pigs) of the TES system likely reflects an adaptive strategy to buffer income variability and manage risk, consistent with the findings of Dumont *et al.* (2020). Finally, management practices, such as early culling and self-administered veterinary treatments, have critical implications for productivity and sustainability. Although early culling may enhance short-term milk output, it can reduce herd reproductive lifespan and long-term productivity (Tschopp *et al.*, 2014; Galina and Geffroy, 2023). Similarly, limited veterinary involvement increases the risk of misdiagnosis and improper medication use, potentially worsening animal health and economic outcomes. The greater reliance on veterinary consultation in the SIS system underscores the benefits of integrating preventive animal health management into traditional production systems (Schrobback *et al.*, 2023). Overall, the results presented in Tables 5 and 6 underscore the need for regional livestock extension programs that integrate training, technical assistance, and participatory innovation. Collaborative efforts among local governments, universities, technological institutes, and nongovernmental organizations (NGOs) could improve pasture management, animal health, and marketing capacities, thereby strengthening the productivity, stability, and resilience of tropical cattle production systems (Maia *et al.*, 2021). The significant differences in income sources, milk destination, and loan allocation among clusters highlight the diversity of livelihood strategies and

investment behaviors across cattle production systems in the Peruvian tropics (Table 7). Producers with more diversified income streams, particularly those combining crop and livestock activities, tend to exhibit greater economic resilience and flexibility in production decisions. These mixed strategies allow farmers to better withstand fluctuations in milk and meat prices, feed costs, and environmental stresses, contributing to household stability. Baker *et al.* (2023) reported similar findings, observing that diversification in mixed farming systems enhances economic sustainability and reduces vulnerability to external shocks. The variation in milk destination across clusters reflects differing market integration and production orientation levels. Traditional systems, such as TES, prioritize self-consumption, reflecting limited market participation and lower production surpluses, whereas semi-intensive and improved systems, such as SIS and IDPES, engage more actively with formal markets and dairy industries. This pattern aligns with that of Bahebeck *et al.* (2023), who documented similar transitions among producers in Cameroon, where SISs gradually shift toward market-oriented milk production to secure more stable income. In addition, the use of acquired loans (0.502) underscores the importance of investment in infrastructure and productive improvements, indicating that access to credit is a crucial factor in system modernization. Producers in the SIS system, who focus on genetic improvement, may be seeking long-term gains in productivity and herd quality. Conversely, TES and IDPES producers prioritize infrastructure and pasture enhancement to improve immediate production capacity and resource efficiency. These differences illustrate the need for differentiated credit schemes that align with each production system's investment priorities and resource capacities. Lyatuu *et al.* (2022) similarly found that targeted investment strategies, ranging from genetic improvement to feed and infrastructure management, positively influence dairy farmers' profitability and poverty reduction in Tanzania.

Overall, these findings reveal substantial heterogeneity in economic behavior, market participation, and investment strategies across cattle production systems. This heterogeneity should inform the design of policies and support programs aimed at promoting financial inclusion, market integration, and sustainable intensification, thereby strengthening the resilience and long-term viability of tropical livestock systems.

Conclusion

This study established typologies and characterized three distinct cattle production systems in the high tropical region (Oxapampa, Chontabamba, and Huancabamba): the traditional extensive system (TES), the SIS, and the IDPES. The results revealed clear differences in the socioeconomic, productive, and management attributes of the participants. This study

highlights the diversity of subsistence strategies among producers and emphasizes the influence of factors such as education, land use, pasture age, pasture species and pest management, agricultural and livestock practices, market orientation, financial behavior, and resource allocation on production efficiency and household resilience. Overall, the results underscore the need for context-specific development strategies tailored to tropical livestock systems.

The results highlight the importance of implementing regional livestock extension programs that integrate technical training, knowledge exchange, and participatory innovation. These programs should focus on enhancing pasture management, reproductive efficiency, genetics, and animal health while strengthening producers' capacity to adapt to climate variability and market uncertainty. Coordinated efforts among government agencies, research institutions, and NGOs are crucial for designing climate adaptation strategies that effectively combine traditional knowledge with modern technologies.

Future research should examine how these production typologies can be integrated with remote sensing and geospatial monitoring tools to identify spatial patterns in pasture conditions, cattle stocking rates, water availability, and land-use change. Integrating farm-level data with remote sensing information could enhance decision-support systems for precision livestock management and inform evidence-based policies aimed at promoting sustainable intensification in tropical regions.

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Authors' contributions

AR-V designed the study, acquired financing, wrote the first draft of the manuscript, and edited and revised the manuscript. JB-L designed the study, conducted the formal analysis, and developed the methodology. EM-R helped with the formal analysis. EAS helped with visualization and edited and revised the manuscript. FH-O helped with project management. FV-G helped with the validation. CB-C performed the statistical analysis, interpreted the results, wrote the original draft of the manuscript, and edited and revised the manuscript.

Conflict of interest

The authors declare no commercial or financial relationships that could be interpreted as potential conflicts of interest.

Data availability

All data were provided in the manuscript.

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