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**Research Article**

**Keywords:** Dairy systems, Zebu cattle, Cross-sectional study, Milk commercialization, Farm typology, Agro-pastoralism, Mauritania, Sahel

**Posted Date:** November 25th, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-11563764/v1

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# Herd scale, production performance and market integration of Moorish zebu (Bos indicus) dairy systems in three Mauritanian regions: a cross-sectional diagnostic study

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## Acknowledgements

We are extremely grateful to the breeders for their active participation in this study. We would also like to thank the technicians and professionals for their invaluable support in data collection. Additionally, we extend our thanks to our colleague Jeyid Yacoub Daye for its support and preparing the study-area map.

## Abstract

Dairy development in Sahelian regions emerges from interactions among herd resources, feeding, management, markets, and territorial infrastructure. These relationships remain poorly characterized for Moorish zebu farms in Mauritania. We examined which system dimensions were associated with reported milk volume and milk-sales revenue and whether recurring farm configurations complemented territorial classifications. A cross-sectional study using non-probability chain-referral recruitment covered 158 farms in Hodh Chargui, Brakna, and Trarza (2023–2024). Regional descriptions, three exploratory log-linear models, principal component analysis, and Ward clustering were applied. Inference is restricted to the surveyed farms. Double milking was reported by 34% of farms in Hodh Chargui, 94% in Brakna, and 91% in Trarza. Mean reported milk yield was 3.14 liters/cow/day, and 41.8% of farms reported zero or negative gross. Adult cow numbers were strongly associated with annual farm milk volume ($\beta$=1.010, $p<0.001$; $R^2$=0.915), indicating scale dependence rather than technical efficiency. Among complete positive cases, milk-sales revenue was associated with feed expenditure ($\beta$=0.498, $p<0.001$) and adult cow numbers ($\beta$=0.234, $p$=0.001). Regional indicators added little explanatory power for milk volume ($\Delta R^2$=0.002). Three provisional configurations were identified among 93 complete cases, but separation was modest (silhouette=0.258) and configuration membership remained associated with region. Herd scale, resource use, management, market connection, and territory therefore represent complementary system dimensions. Interventions should combine repeated recording, feed and reproductive management, milk collection, and extension tailored jointly to farm configuration and territory. Representative longitudinal data are required before national scaling or causal claims.

**Keywords:** Dairy systems; Zebu cattle; Cross-sectional study; Milk commercialization; Farm typology; Agro-pastoralism; Mauritania; Sahel

## Introduction

Dairy farming systems are shaped by coupled biological, technical, economic, and institutional processes (Thornton, 2010).

In low- and middle-income countries, rising demand for animal-source foods creates opportunities for rural income and food supply, but outcomes depend on how herd resources, feed, labor, infrastructure, and markets interact rather than on any single component (Delgado et al., 1999). A systems perspective is therefore needed to distinguish farm scale, technical management, commercialization, and territorial context.

These interactions are especially important in arid and semi-arid livestock systems, where climatic variability, seasonal feed shortages, herd mobility, and uneven access to collection and processing infrastructure jointly shape production and marketing (Sraïri et al., 2007; Molina-Flores et al., 2020; Eeswaran et al., 2022). Evidence from African dairy systems also shows that proximity to markets and service centers can alter both farming intensity and market participation, making connectivity a core system attribute rather than a simple location effect (van der Lee et al., 2020).

In Mauritania, livestock contributes about 10% of national gross domestic product, and the national cattle population is estimated at 6,147,638 head (ANSADE, 2025). Moorish zebu dairying links pastoral and agro-pastoral resource use to rapidly evolving urban milk markets. However, quantitative evidence remains limited on how farm resource endowment, herd management, expenditure, milk production, and commercialization combine across the principal dairy regions. Previous work has mainly been descriptive or region-specific (El Hadj et al., 2024), while studies elsewhere in West Africa have documented substantial within-region heterogeneity and market-driven differentiation of livestock systems (Habanabakize et al., 2022; Vall et al., 2021; Orounladji et al., 2025).

Farm typologies can summarize such heterogeneity and support the targeting of research, extension, and policy, but their usefulness depends on a clearly defined purpose, appropriate variables, and validation in the intended decision context (Cortez-Arriola et al., 2015; Huber et al., 2024; Manners et al., 2025). For Mauritanian dairying, a functional typology should complement rather than replace territorial analysis because farms operate within contrasting feed, water, service, and milk-collection environments.

A further methodological challenge is farm access. Updated sampling frames are scarce, herds may be mobile, and trusted social or professional introductions often determine survey participation (Mballo et al., 2019; Catley et al., 2016; FAO, 2018). Adapted recruitment can broaden access, but chain-referral samples are not probability samples and cannot support nationally representative estimates without network-degree information, weighting, and stronger sampling frames. Despite the economic importance of Moorish zebu dairy systems, no published study has simultaneously characterized scale, management, commercialization, and territorial dimensions across multiple Mauritanian regions using farm-level quantitative data.

Against this background, the study addressed three systems questions: (i) which technical, demographic, and economic components differed across the three surveyed dairy territories; (ii) which measured farm components were conditionally associated with reported annual milk volume and positive milk-sales revenue; and (iii) whether recurring farm configurations could be identified across regions. We expected total farm milk volume to be dominated by herd scale, commercial outcomes to reflect a different combination of herd size, feed expenditure, and management, and regional context to remain relevant but incompletely represented by measured farm variables. These expectations guided an exploratory diagnosis rather than causal hypothesis testing. To our knowledge, this is the first multi-region Mauritanian study to integrate production, commercialization, regional context, and farm typology within one analytical framework.

## Materials and Methods

### Systems framework and analytical strategy

The surveyed farm was treated as a production–commercialization system nested within a regional dairy territory. The framework separated five dimensions that should not be conflated: territorial opportunity and constraint structures; herd scale and demographic composition; biological and management processes; commercialization and economic outcomes; and recurring multivariate configurations. The analysis combined regional description, diagnostic association models, and exploratory configuration analysis. Box 1 links each dimension to the available indicators and states the inferential boundary imposed by the cross-sectional, non-probability design.

**Box 1. Systems framework and inferential boundaries.**

| System dimension | Indicators available | Analytical use | Inferential boundary |
|---|---|---|---|
| Territory and market environment | Region, dairy infrastructure, distance to urban center | Contextual comparison and residual regional model | Region is a proxy; infrastructure and access effects are not identified causally. |
| Herd resources | Total herd, adult cows, sex and age composition | Scale description, M1/M3, PCA | Total volume is scale-dependent and is not a measure of technical efficiency. |
| Biology and management | Daily yield, lactation, inter-calving interval, milking frequency | Regional description, M2, PCA | Self-reported cross-sectional indicators do not estimate management effects. |
| Commercialization and economics | Milk sold, expenditure, revenue, gross margin | Descriptive economics and conditional revenue model | Revenue combines participation, quantity, and price; zero-revenue farms are not modelled separately. |
| Farm configuration | PCA scores and Ward clusters | Hypothesis generation for differentiated sampling and extension | Clusters are provisional and require stability, participatory, and external validation. |

## Geographic context and description of study area

The study was conducted in the three main dairy basins of Mauritania (Fig. 1), whose biophysical characteristics are presented in Table 1. Hodh Chargui, in the south-east, is dominated by an extensive pastoral system characterized by herd mobility, large cattle numbers, and Moorish and Fulani pastoral communities. It is characterized by low milk commercialization due to limited dairy infrastructure and a relatively short history in the dairy sector. Brakna, in the south-west, is dominated by an agro-pastoral system based on complementarity between crop farming and livestock rearing, principally along the tributaries of the Senegal River. Trarza, also in the south-west, benefits from permanent access to water and abundant fodder resources thanks to the Senegal River, and constitutes the region most integrated into the national dairy market. Trarza also concentrates the main milk collection and processing infrastructure. These territorial contrasts influence feeding strategies, herd management practices, and the technical and economic performance of farms. Together, these three regions account for 2,936,612 cattle, representing 48% of the national herd estimated at 6,147,638 head (ANSADE 2025).

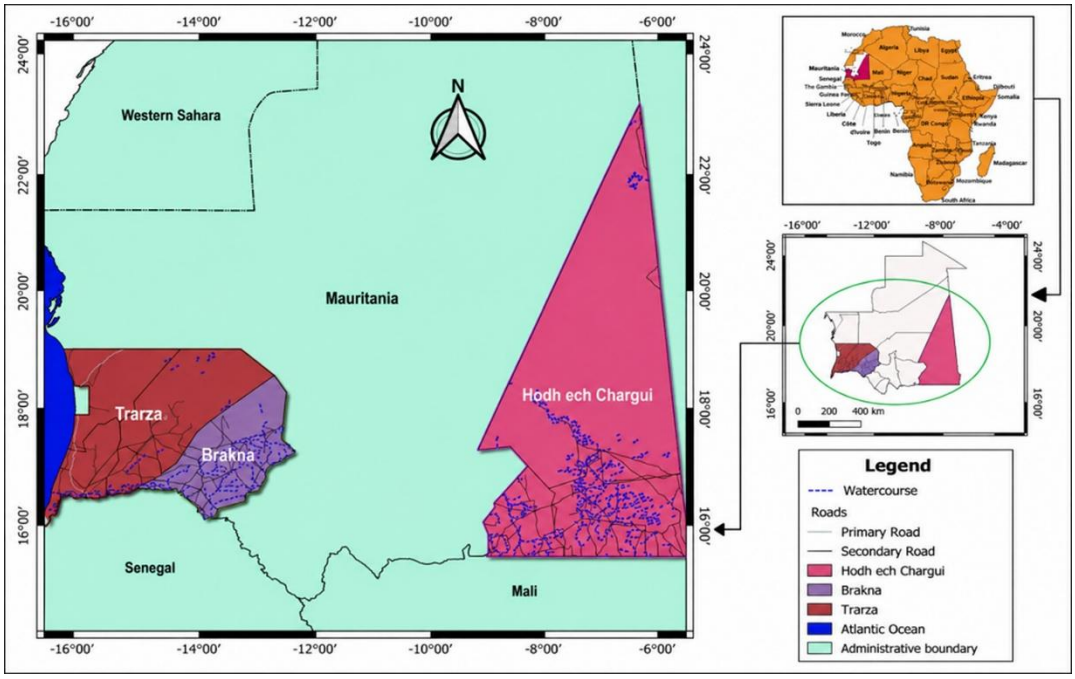


**Fig. 1. Study regions and dairy territories in Mauritania.**

**Table 1. Biophysical and infrastructural characteristics of the research location**
**Sources : ANSADE (2025) and ONM (2022)**

| Parameter | Hodh Chargui | Brakna | Trarza |
|---|---|---|---|
| Location | 16°33'59"N/7°10'33"W | 17°03′39″N/3°54′42″W | 17°58′31″N/14°44′04″W |
| Altitude (m.a.s.l) | 325 | 75 | 36 |
| Area (ha) | 18,270,000 | 3,380,000 | 6,780,000 |
| Climate | Sahelo-Saharan | Sahelian/Sub-Saharan | Tropical/Sahelo-Saharan |
| Annual rainfall (mm) | 200-400 | 200-300 | 100-300 |
| Rainfall regime | Unimodal and irregular | Unimodal and irregular | Unimodal and irregular |
| Rainfall period | June-October | June-October | July-October |
| Temperature range (°C) | 18-45 | 18-45 | 20-40 |
| Cattle population (head) | 1,983,058 | 390,990 | 562,564 |
| Livestock production System | Pastoral livestock farming | Mixed livestock and crop farming | Mixed livestock and crop farming |
| Dairy infrastructure | Recent public | Long-established private | Long-established private |
| Distance to urban center (km) | 5-105 | 5-85 | 5-110 |

## Sampling protocol and survey method

Farm surveys in mobile agro-pastoral settings are constrained by incomplete registers, seasonal herd mobility, and

the importance of trusted networks for gaining access to respondents (Mballo et al., 2019; Catley et al., 2016; FAO, 2018). Under these conditions, probability sampling is difficult, whereas uncontrolled convenience or snowball recruitment may overrepresent closely connected farm networks.

The study used stratified chain-referral recruitment, informed by respondent-driven sampling principles but without population-degree measurement or Volz-Heckathorn weighting (Heckathorn, 1997; Volz and Heckathorn, 2008). Recruitment was conducted separately in Hodh Chargui, Brakna, and Trarza. Five initial participants (seeds) per region were identified with support from livestock services, milk collection centers, and professional organizations. Eligible participants managed farms predominantly keeping Moorish zebu, were active in milk production during the reference period, and consented to participate. Farms were retained whether they sold milk or not, and reported zero sales were treated as valid descriptive observations. Regional quotas and referral progression were monitored to reduce concentration in a single network. Because degree-based weights and a complete sampling frame were unavailable, the sample is non-probabilistic and not nationally representative.

Recruitment stability was explored by comparing five measured characteristics between the fourth and fifth recruitment waves. Relative changes below 5% and non-significant Welch tests suggested similar late-wave values for those characteristics. This was treated only as a recruitment diagnostic; it neither eliminates selection bias nor establishes representativeness. The final sample comprised 50 farms in Hodh Chargui, 51 in Brakna, and 57 in Trarza (158 farms in total; Fig. 2).

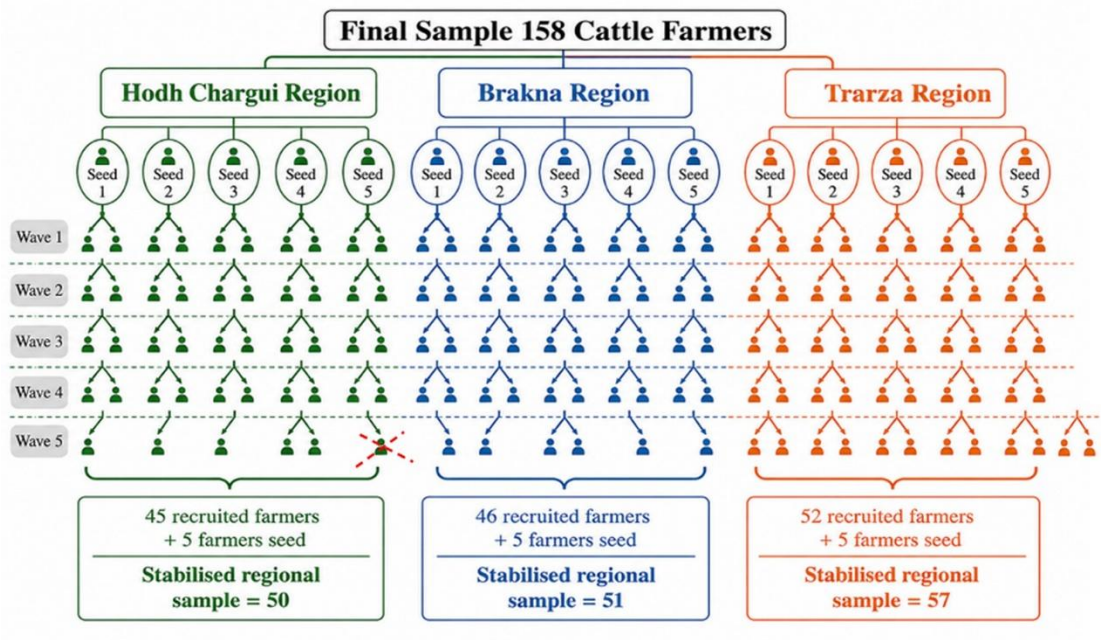


**Fig. 2. Stratified chain-referral recruitment by region and seed.**

**Variables and component-wise comparisons**

Surveys were conducted from July 2023 to May 2024 using a structured, semi-open questionnaire administered face to face; interviews lasted approximately 30-45 min. Thirty variables were organized into four thematic blocks (Table 2). Production, cost, and revenue variables were self-reported, and the survey did not systematically distinguish audited records from farmer estimates. Milking frequency was coded 1=single and 2=double and treated as a binary management indicator. Exact double-milking counts were 17/50 in Hodh Chargui, 48/51 in Brakna, and 52/57 in Trarza, giving 117/158 (74.1%) overall. Continuous variables were summarized using means, standard deviations, medians, and ranges. Because recruitment was non-probabilistic, regional comparisons were treated as exploratory descriptions. One-way ANOVA and $\eta^2$ were retained only as model-based summaries for continuous variables. Strongly skewed economic variables are presented using means and medians, without population-level significance claims.

All tests were two-sided with $\alpha=0.05$. Referral-network dependence could make conventional standard errors optimistic; p-values and confidence intervals are therefore interpreted as exploratory model-based quantities within the surveyed sample, not as design-based population inference. Emphasis is placed on effect magnitude, internal consistency, and uncertainty. Annual milk volume, milk sales, costs, and revenues were treated as separate self-reported farm-level variables; because recall and derivation could not be independently audited, the regression models are used as diagnostics rather than production functions.

**Table 2. Variables collected and their analytical roles.**

| Thematic block | Variable | Type | Unit/Modality |
|---|---|---|---|
| 1. Socio-demographic profile (5) | Farmer sex | Nominal | % |
| | Farmer age | Quantitative | years |
| | Household size | Quantitative | persons |
| | Education level | Ordinal | Code 1-5* |
| | *code 1=None, code 2=Quranic, code 3=Primary, code 4=Secondary, code 5=Higher | | |
| | Farming experience category | Ordinal | Code 1-6* |
| | *code 1=<5, code 2=5–10, code 3=10–15, code 4=15–20, code 5=20–25, code 6=>25 | | |
| 2. Herd structure (6) | Total herd size | Quantitative | head |
| | Adult cows | Quantitative | head |
| | Females (%) | Quantitative | % |
| | Adults (%) | Quantitative | % |
| | Adult females (%) | Quantitative | % |
| | Calves (%) | Quantitative | % |
| 3. Reproduction and production (10) | Lactation length | Quantitative | months |
| | Inter-calving interval | Quantitative | years |
| | Milk yield per cow per day | Quantitative | liters/day |
| | Daily milking frequency | Ordinal | single/double |
| | Annual milk production per farm | Quantitative | tons/year |
| | Annual milk sold | Quantitative | tons/year |
| | Age at male puberty | Quantitative | years |
| | Age at female puberty | Quantitative | years |
| | Age at first calving | Quantitative | years |
| | Age at weaning | Quantitative | months |
| 4. Farm economics (9) | Feed cost | Quantitative | MRU/year |
| | Labor cost | Quantitative | MRU/year |
| | Water cost | Quantitative | MRU/year |
| | Veterinary cost | Quantitative | MRU/year |
| | Total cost | Quantitative | MRU/year |
| | Revenue from milk sales | Quantitative | MRU/year |
| | Total revenue | Quantitative | MRU/year |
| | Gross margin | Quantitative | MRU/year |
| | Gross margin per adult cow | Quantitative | MRU/year |

**Diagnostic association models and inferential boundaries**

Three log-linear specifications examined conditional relationships among measured farm-system components and two outcomes: reported annual farm milk volume and annual milk-sales revenue. The models are descriptive diagnostics, not causal production functions, because inputs and outcomes were measured simultaneously and recruitment was non-probabilistic (Henningsen et al., 2026). M1 decomposes total farm volume and is dominated by the arithmetic effect of herd scale. M2 describes revenue intensity only among farms with positive revenue and complete positive covariates; it does not model the probability of market participation. M3 asks whether residual regional associations remain after adjustment for the measured farm factors. Here, the Cobb-Douglas specification is used exclusively for its convenient log-linear form, transforming multiplicative relationships among positive-valued farm variables into easily interpretable percentage-based coefficients. It is not employed to estimate structural

production elasticities. The cross-sectional, non-probabilistic design does not satisfy the identifying assumptions required for a causal production-function interpretation. Its multiplicative form is given by the equation (1):

$$Y_i = AX_{1i}^{\beta_1} * X_{2i}^{\beta_2} * X_{3i}^{\beta_3} * X_{4i}^{\beta_4} * e^{\varepsilon_i} \qquad (1)$$

Here, Y is the outcome, A is the intercept, $X_j$ are measured farm factors, $\beta_j$ are regression coefficients, and $\varepsilon_i$ is the residual. After logarithmic transformation, coefficients for positive continuous variables are conditional elasticities.

$$\ln(Y_i) = \alpha + \beta_1 \ln(X_{1i}) + \beta_2 \ln(X_{2i}) + \beta_3 \ln(X_{3i}) + \beta_4 \ln(X_{4i}) + \varepsilon_i \qquad (2)$$

Models were estimated by ordinary least squares on complete cases with strictly positive values for every logged variable; no offset was added. This yielded n=126 for M1 and M3 and n=119 for M2. Coefficients for log-transformed variables are log-elasticities; coefficients for untransformed (linearly entered) variables give the additive effect per unit on the log outcome, not an elasticity; the coefficient for the milking-frequency variable gives the log-difference in yield per additional daily milking; it is not an elasticity. Variance inflation factors are reported, and HC3 robust standard errors were used in the retained output (HC3 was preferred over HC1 because it provides more conservative inference in small to moderate samples by applying a leverage correction that down-weights high-influence observations). Recruitment-chain clustered errors, formal influence diagnostics, and a two-part commercialization model (Cragg, 1971) were unavailable; this limitation is reflected in the restricted interpretation of all models.

M1 related reported annual milk volume to adult cow numbers and annual feed, hired-labor, and veterinary expenditures. Because total volume aggregates milk across cows, the adult-cow coefficient is interpreted as farm-scale dependence, not productivity. M2 related positive milk-sales revenue to adult cow numbers, feed expenditure, milking frequency, veterinary expenditure, and lactation length. Revenue combines market participation, marketed quantity, and price, so M2 describes conditional commercialization intensity rather than technical returns. M3 extended M1 with regional indicators for Brakna and Trarza, using Hodh Chargui as the reference.

**M1: Scale diagnostic for reported annual farm milk volume (n=126)**

M1 examined how reported annual farm milk volume varied with adult cow numbers and annual feed, hired-labor, and veterinary expenditures (Equation 3). The adult-cow coefficient quantifies scale dependence and is not interpreted as technical efficiency, biological productivity, or a causal benefit of herd expansion. Its form is given by the equation (3):

$$\ln(Y) = \alpha + \beta_1 \ln(\text{Cow}) + \beta_2 \ln(\text{Feed}) + \beta_3 \ln(\text{Lab}) + \beta_4 \ln(\text{Vet}) + \varepsilon \qquad (3)$$

Y is annual milk production (tons/year); Cow is the number of adult cows; Feed, Lab, and Vet are annual expenditures on feed, hired labor, and veterinary services, respectively.

**M2: Conditional milk-sales revenue among positive-revenue farms (n=119)**

M2 examined associations with positive annual milk-sales revenue among farms with complete positive values (Equation 4). Because revenue reflects participation, marketed quantity, and price, coefficients are commercial associations rather than causal returns to individual inputs. The model does not explain why some farms did not sell milk. Its form is given by the equation (4):

$$\ln(Y) = \alpha + \beta_1 \ln(Cow) + \beta_2 \ln(Feed) + \beta_3 \ln(Milking) + \beta_4 \ln(Vet) + \beta_5 \ln(Lact) + \varepsilon \qquad (4)$$

Y is annual milk-sales revenue (MRU/year); Milking is a binary indicator coded 1 for single and 2 for double daily milking; and Lact is lactation length (months).

**M3: Residual regional association after measured farm factors (n=126)**

M3 extended M1 by adding indicators for Brakna and Trarza, with Hodh Chargui as the reference region. It tested whether residual regional differences in annual milk volume were detectable after adjustment for the measured farm factors. Non-significant regional coefficients are interpreted as absence of evidence in this sample, not as proof that territorial conditions are irrelevant. Its form is given by the equation (5):

$$\ln(Y) = \alpha + \beta_1 \ln(Cow) + \beta_2 \ln(Feed) + \beta_3 \ln(Lab) + \beta_4 \ln(Vet) + \delta_{Bk} * D_{Bk} + \delta_{TZ} * D_{TZ} + \varepsilon \qquad (5)$$

where D_BK and D_TZ are indicators for Brakna and Trarza, and δ_BK, δ_TZ are their conditional differences relative to Hodh Chargui.

**Exploratory multivariate dimensions and farm configurations**

Principal component analysis (PCA) was performed on 18 standardized variables representing household resources, herd scale and composition, milk management and production, expenditure, commercialization, revenue, and margin. Several variables are mathematically or accounting-related (for example, herd size and adult cow numbers; component costs and total cost; revenues and gross margin). PCA was therefore used to compress the observed covariance structure, not to identify independent latent causal constructs. Bartlett's test and the Kaiser–Meyer–Olkin index assessed suitability. Five components with eigenvalues>1 were retained, and Ward clustering with Euclidean distance was applied to their scores. The analysis used 93 complete cases; 65 farms were excluded, especially because

of missing annual milk sold and household size. No imputation, bootstrap stability analysis (Hennig, 2007), participatory validation, or external validation was available. The three-configuration solution was evaluated descriptively using the mean silhouette coefficient (Rousseeuw, 1987) and treated as hypothesis-generating. The Kaiser rule was used only as an operational dimension-reduction criterion; because parallel analysis (Horn, 1965) and resampling were not performed, the number of retained components should not be interpreted as uniquely established.

### Data processing and analysis

Analyses were conducted in Python 3.12.3 using pandas, NumPy, SciPy, Matplotlib, scikit-learn, and openpyxl. The de-identified analytical data, data dictionary, and analysis code are maintained by the authors and are available from the corresponding author upon reasonable request, subject to farm-confidentiality safeguards.

## Results

### Component heterogeneity across surveyed dairy systems

The survey included 158 farms, 50 in Hodh Chargui, 51 in Brakna, and 57 in Trarza, reporting a total of 29,636 cattle: 11,431, 9,269, and 8,936, respectively. Results are organized first by system component, then by diagnostic relationships among components, and finally by exploratory multivariate configurations. Regional comparisons describe patterns within the surveyed farms and are not population estimates.

### Household and managerial context

Five socio-demographic variables described the farm manager and household context. They provide information on human capital and potential family labor, but they do not directly measure labor productivity or the contribution of all household members.

Farm managers were predominantly men (91.8%) and had a mean age of 53.2±11.9 years. More than 71% reported over 25 years of experience, and primary education was the most common level (57.7%). Household size showed the clearest regional difference ($F=16.48$, $p<0.001$, $\eta^2=0.195$), with larger households in Hodh Chargui. Because the questionnaire focused on the principal manager, it probably under-recorded women's roles in milking, processing, and marketing.

### Herd resource base and demographic structure

Herd structure described farm scale and demographic composition. Mean values and exploratory regional comparisons are presented in Table 3.

**Table 3. Herd scale and demographic composition in the surveyed farms**

| Variable | Over all | | | | | Regions | | | F* | Sig.* | η²* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | n | Mean±SD | Min | Med. | Max | HC (n=50) | BK (n=51) | TZ (n=57) | | | |
| Total herd (head) | 157 | 188.8±278.3 | 6 | 84 | 1,590 | 233.3 | 181.8 | 156.8 | 1.02 | ns | 0.013 |
| Adult cows (head) | 156 | 88.1±129.3 | 3 | 40 | 750 | 104.8 | 72.2 | 88.0 | 0.79 | ns | 0.010 |
| % Females | 157 | 81.2±8.28 | 46.8 | 81.5 | 100 | 80.7 | 77.8 | 84.6 | 10.09 | *** | 0.116 |
| % Adults | 156 | 50.3±14.1 | 15.3 | 49.2 | 87.0 | 53.1 | 43.6 | 53.9 | 9.35 | *** | 0.109 |
| % Adult females | 156 | 48.4±14.1 | 14.4 | 47.0 | 87.0 | 49.9 | 42.2 | 52.7 | 8.74 | *** | 0.103 |
| % Calves | 156 | 24.3±8.31 | 5.6 | 24.5 | 50.0 | 22.4 | 26.8 | 23.6 | 3.86 | * | 0.048 |

HC: Hodh Chargui; BK: Brakna; TZ: Trarza; Med.: median. F and $\eta^2$ are exploratory model-based statistics; ns: $p\geq0.05$; *$p<0.05$; ***$p<0.001$.

Farm scale varied widely within regions: mean herd size was 188.8 head and mean adult cow number was 88.1. Regional contrasts were clearer for herd composition than for scale. The proportions of females, adults, and adult females were higher in Trarza and Hodh Chargui than in Brakna ($\eta^2=0.10$–$0.12$), whereas the contrast in calf proportion was smaller ($\eta^2=0.048$).

### Reproduction, milking management, and milk production

Table 4 summarizes self-reported reproductive and productive indicators. Recall and measurement error are possible because standardized animal-level recording was not available.

**Table 4. Reproductive, management, and milk-production indicators in the surveyed farms**

| Variable | Over all | | | | | Régions | | | F* | Sig.* | η²* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | n | Mean±SD | Min | Med. | Max | HC (n=50) | BK (n=51) | TZ (n=57) | | | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lactation length (months) | 156 | 7.16±2.14 | 2 | 7 | 12 | 6.52 | 7.71 | 7.25 | 4.07 | * | 0.051 |
| Inter-calving interval (years) | 155 | 1.26±0.37 | 1 | 1 | 2 | 1.40 | 1.18 | 1.21 | 5.34 | ** | 0.066 |
| Milk yield/cow/day (liters) | 154 | 3.14±0.71 | 1.5 | 3.0 | 6.0 | 3.38 | 3.02 | 3.04 | 4.16 | * | 0.052 |
| Milking frequency (% double) | 158 | 74.1% | 1 | 2 | 2 | 34 | 94 | 91 | — | — | — |
| Annual milk/farm (t/year) | 152 | 62.4±91.4 | 1.5 | 27.6 | 540 | 71.3 | 58.7 | 58.1 | 0.32 | ns | 0.004 |
| Annual milk sold (t/year) | 115 | 22.3±27.5 | 0 | 10.8 | 144 | 19.1 | 23.3 | 24.2 | 0.37 | ns | 0.007 |
| Age at male puberty (years) | 156 | 3.09±0.42 | 2 | 3 | 5 | 3.19 | 3.06 | 3.04 | 2.03 | ns | 0.027 |
| Age at female puberty (years) | 157 | 3.16±0.43 | 2 | 3 | 4 | 3.07 | 3.16 | 3.24 | 2.11 | ns | 0.026 |
| Age at first calving (years) | 156 | 4.16±0.43 | 3 | 4 | 5 | 4.07 | 4.16 | 4.25 | 2.36 | ns | 0.030 |
| Age at weaning (months) | 155 | 9.53±2.31 | 4 | 10 | 15 | 10.24 | 9.49 | 8.95 | 4.37 | * | 0.054 |

Milking frequency showed the clearest descriptive regional contrast: double milking was reported by 17/50 farms (34%) in Hodh Chargui, 48/51 (94%) in Brakna, and 52/57 (91%) in Trarza, for 117/158 farms (74.1%) overall. Hodh Chargui also had a longer reported inter-calving interval and a shorter lactation. Mean daily milk yield was 3.14 liters per cow, with a small regional effect ($\eta^2$=0.052). Annual farm milk volume and annual milk sold varied substantially within regions and showed no clear regional separation in this non-probability sample.

**Costs, revenues, and economic vulnerability**

Economic variables were strongly skewed; both means and medians are therefore reported. Table 5 summarizes annual costs, revenues, and gross margins in Mauritanian ouguiya (MRU).

**Table 5. Annual farm costs, revenues, and gross margins (MRU/year)**

| Variable (MRU/year) | Over all | | | | | Regions | | |
|---|---|---|---|---|---|---|---|---|
| | n | Mean±SD | Median | Min | Max | HC (n=50) | BK (n=51) | TZ (n=57) |
| Feed cost | 158 | 341,649±462,600 | 174,000 | 3,920 | 2,700,000 | 166,652 | 447,961 | 400,033 |
| Labor cost | 146 | 191,885±267,661 | 108,000 | 9,000 | 800,000 | 214,773 | 194,468 | 171,367 |
| Water cost | 158 | 9,172±18,164 | 0 | 0 | 80,000 | 8,180 | 18,469 | 1,724 |
| Veterinary cost | 158 | 14,340±25,911 | 4,500 | 0 | 190,000 | 13,935 | 9,675 | 18,870 |
| Total cost | 158 | 547,599±666,674 | 285,500 | 7,000 | 3,953,000 | 377,767 | 671,202 | 585,981 |
| Milk sales revenue | 158 | 508,883±679,282 | 241,920 | 0 | 3,744,000 | 346,651 | 661,096 | 515,002 |
| Total revenue | 158 | 995,726±2,138,054 | 358,400 | 0 | 23,844,000 | 855,175 | 1,338,369 | 812,441 |
| Gross margin | 158 | 448,127±1,760,548 | 74,560 | −1,037,800 | 19,891,000 | 477,407 | 667,167 | 226,460 |
| Gross margin per cow | 157 | 5,408±14,418 | 1,893 | −32,360 | 99,455 | 4,256 | 8,830 | 3,337 |

Feed and water expenditures showed the largest descriptive regional contrasts. Other costs, revenues, and margins varied substantially within regions. Gross margin was strongly right-skewed: the mean was 448,127 MRU/year, the median was 74,560 MRU/year, and 41.8% of farms reported a zero or negative margin. This vulnerability is more informative than a comparison of regional means alone.

**Diagnostic associations among measured system components**

**M1: Scale diagnostic for annual farm milk volume**

M1 explained 91.5% of variation in reported annual farm milk volume ($R^2$=0.9151). Adult cow numbers had a near-

unit coefficient (β=1.010, p<0.001), whereas feed, labor, and veterinary expenditures were not statistically distinguishable from zero. The high $R^2$ and near-unit coefficient are primarily expected consequences of aggregating milk across more cows (table 6). They should not be read as evidence of technical efficiency, biological productivity, or a causal benefit of herd expansion. The absence of per-cow yield (L/cow/day) as a regressor means M1 cannot discriminate between scale-driven and per-animal productivity-driven volume increases a distinction with direct implications for intervention design. The estimated multiplicative equation is:

$$Y_1 = 0.3603 * Cow^{1.010} * Feed^{0.067} * Lab^{-0.004} * Vet^{-0.029}$$

**Table 6. M1 scale diagnostic for reported annual farm milk volume (n=126)**

| Parameter | β | SE | t-stat | p-value | Sig. | 95% CI | VIF |
|---|---|---|---|---|---|---|---|
| α = constant | −1.0209 | 0.5224 | −1.955 | 0.053 | ns | [−2.055 ; 0.013] | — |
| $\beta_1$: Adult cows (head) | 1.0099 | 0.0444 | 22.75 | <0.001 | *** | [+0.922 ; 1.098] | 2.308 |
| $\beta_2$: Feed cost (MRU) | 0.0670 | 0.0389 | 1.721 | 0.088 | ns | [−0.010 ; 0.144] | 2.227 |
| $\beta_3$: Labor cost (MRU) | −0.0040 | 0.0538 | −0.074 | 0.941 | ns | [−0.111 ; 0.103] | 2.622 |
| $\beta_4$: Veterinary cost (MRU) | −0.0291 | 0.0242 | −1.203 | 0.231 | ns | [−0.077 ; 0.019] | 1.038 |

SE: standard error; CI: confidence interval; VIF: variance inflation factor. Coefficients are conditional associations in complete positive cases; p-values are exploratory within the surveyed sample.

**M2: Conditional positive milk-sales revenue**

Among positive-revenue farms with complete positive covariates, M2 explained 64.0% of variation in annual milk-sales revenue ($R^2$=0.6404). Feed expenditure (β=0.498, p<0.001) and adult cow numbers (β=0.234, p=0.001) were positively associated with revenue; milking frequency, lactation length, and veterinary expenditure were not statistically distinguishable from zero (table 7). Because zero-revenue farms were excluded, this is a conditional model of revenue intensity after market entry, not a model of participation. This selection on positive outcomes may introduce upward bias in feed-expenditure coefficients if high-spending farms are also more likely to sell milk; a two-part (Cragg) or Heckman selection model would provide a joint estimate of market participation and revenue intensity without this truncation. Feed expenditure may reflect feeding intensity, herd scale, market orientation, input prices, or reverse causation. The estimated multiplicative equation is:

$$Y_2 = 500.78 * Cow^{0.234} * Feed^{0.498} * Milking^{0.279} * Vet^{-0.081} * Lact^{0.068}$$

**Table 7. M2 conditional model of positive annual milk-sales revenue (n=119)**

| Parameter | β | SE | t-stat | p-value | Sig. | 95% CI | VIF |
|---|---|---|---|---|---|---|---|
| α = constant | 6.2162 | 0.8711 | 7.136 | <0.001 | *** | [+4.490 ; 7.942] | — |
| $\beta_1$: Adult cows (head) | 0.2340 | 0.0690 | 3.391 | 0.001 | ** | [+0.097 ; 0.371] | 1.837 |
| $\beta_2$: Feed cost (MRU) | 0.4984 | 0.0672 | 7.419 | <0.001 | *** | [+0.365 ; 0.632] | 1.952 |
| $\beta_3$: Double-milking indicator (1=no; 2=yes) | 0.2789 | 0.2338 | 1.193 | 0.235 | ns | [−0.184 ; 0.742] | 1.327 |
| $\beta_4$: Veterinary cost (MRU) | −0.0805 | 0.0429 | −1.879 | 0.063 | ns | [−0.165 ; 0.004] | 1.051 |
| $\beta_5$: Lactation length (months) | 0.0680 | 0.2319 | 0.293 | 0.770 | ns | [−0.391 ; 0.528] | 1.282 |

SE: standard error; CI: confidence interval; VIF: variance inflation factor. The model excludes zero-revenue observations and is conditional on complete positive cases. Coefficients are associative, and p-values are exploratory within the surveyed sample.

**M3: Residual regional association in annual milk volume**

Adding regional indicators to M1 increased $R^2$ by only $\Delta R^2$=0.002. Neither the Brakna nor Trarza coefficient was statistically distinguishable from the Hodh Chargui reference after adjustment for the measured inputs (table 8). This indicates an absence of detectable residual regional association in the fitted sample, not proof that infrastructure, ecology, feed access, or market conditions are unimportant. Some regional differences may already be absorbed by the measured covariates (herd size, feed costs) if these variables are regionally stratified, which would attenuate the residual regional indicator coefficients even when true territorial differences exist. The estimated multiplicative form is:

$$Y_3 = 0.44 * Cow^{1.037} * Feed^{0.035} * Lab^{-0.003} * Vet^{-0.030} * \exp(0.169 D_{BK}) * \exp(0.089 D_{TZ})$$

**Table 8. M3 residual regional association in annual milk volume (n=126)**

| Parameter | β or δ | SE | t-stat | p-value | Sig. | 95% CI | VIF |
|---|---|---|---|---|---|---|---|
| α = constant | −0.8203 | 0.5330 | −1.539 | 0.126 | ns | [−1.876 ; 0.235] | — |
| $\beta_1$: Adult cows (head) | 1.0375 | 0.0470 | 22.061 | <0.001 | *** | [0.944 ; 1.131] | 2.308 |
| $\beta_2$: Feed cost (MRU) | 0.0347 | 0.0430 | 0.807 | 0.422 | ns | [−0.051 ; 0.120] | 2.227 |
| $\beta_3$: Labor cost (MRU) | −0.0034 | 0.0536 | −0.064 | 0.949 | ns | [−0.110 ; 0.103] | 2.622 |
| $\beta_4$: Veterinary cost (MRU) | −0.0302 | 0.0246 | −1.229 | 0.221 | ns | [−0.079 ; 0.018] | 1.038 |
| δ_BK: Brakna indicator | 0.1691 | 0.0987 | 1.734 | 0.086 | ns | [−0.024 ; 0.362] | — |
| δ_TZ: Trarza indicator | 0.0891 | 0.0857 | 1.039 | 0.297 | ns | [−0.079 ; 0.258] | — |

SE: standard error; CI: confidence interval; VIF: variance inflation factor. Regional coefficients compare Brakna and Trarza with Hodh Chargui within the fitted complete-positive sample. P-values are exploratory, not design-based population inference.

**Multivariate system configurations**

**Exploratory covariance structure**

Among 93 complete cases, PCA produced KMO=0.612 and a significant Bartlett test ($\chi^2$=2,300.09; df=153; p<0.001). Five components with eigenvalues >1 explained 76.1% of total variance. Because KMO was moderate, 65 farms were excluded, and several variables were accounting-related, the components are interpreted as descriptive covariance dimensions rather than independent latent constructs. Because exchangeability between the complete-case subset and the 65 excluded farms was not established, these multivariate results apply only to the 93 complete cases. A supplementary comparison of key characteristics (herd size, reported milk yield, region) between the 93 included and 65 excluded farms is recommended; systematic differences would further restrict the interpretation of the identified configurations. Five components exceeded the Kaiser criterion, a result also consistent with Horn's parallel analysis (Horn, 1965), which confirmed five components with eigenvalues exceeding the corresponding parallel random-data eigenvalues, and together explained 76.1% of variance among 93 complete cases (Figure 3).

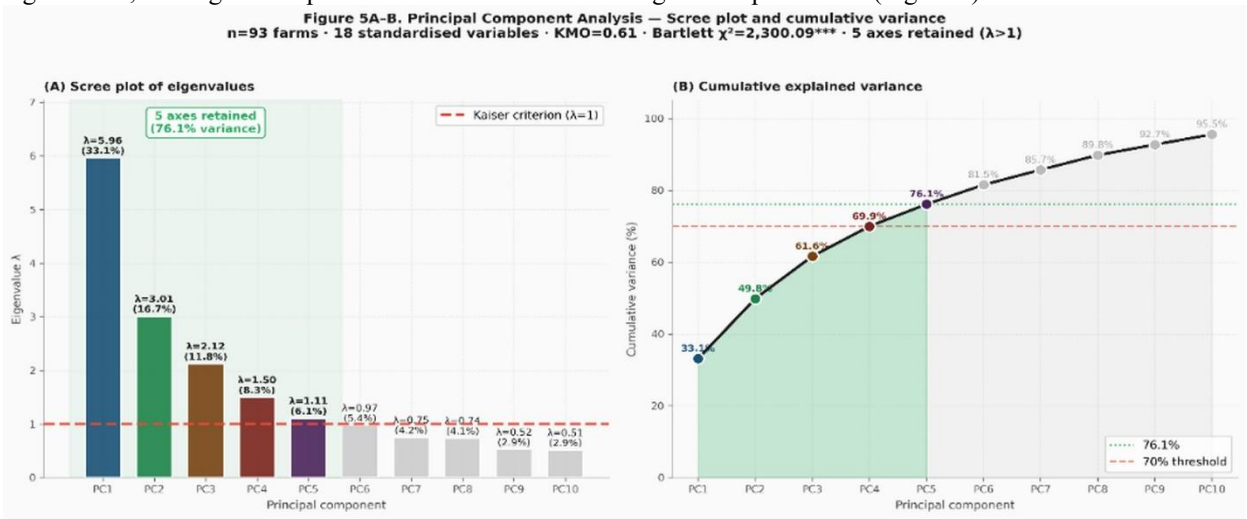


**Fig. 3. PCA eigenvalue spectrum and cumulative variance.**

Vectors show the direction and strength of correlations between observed variables and the principal-component space; the axes are descriptive covariance dimensions (Figure 4). PC1 (33.1%) summarized the expected covariance of farm scale, milk volume, revenues, and costs. PC2 (16.7%) represented herd demographic structure. PC3 (11.8%) combined management and commercialization, including milking frequency and lactation length. PC4 (8.3%) contrasted gross margin and feed expenditure, and PC5 (6.1%) was dominated by reproductive indicators. These axes separate observed dimensions for description, but their interpretation partly reflects the mathematical and accounting relationships among the input variables.

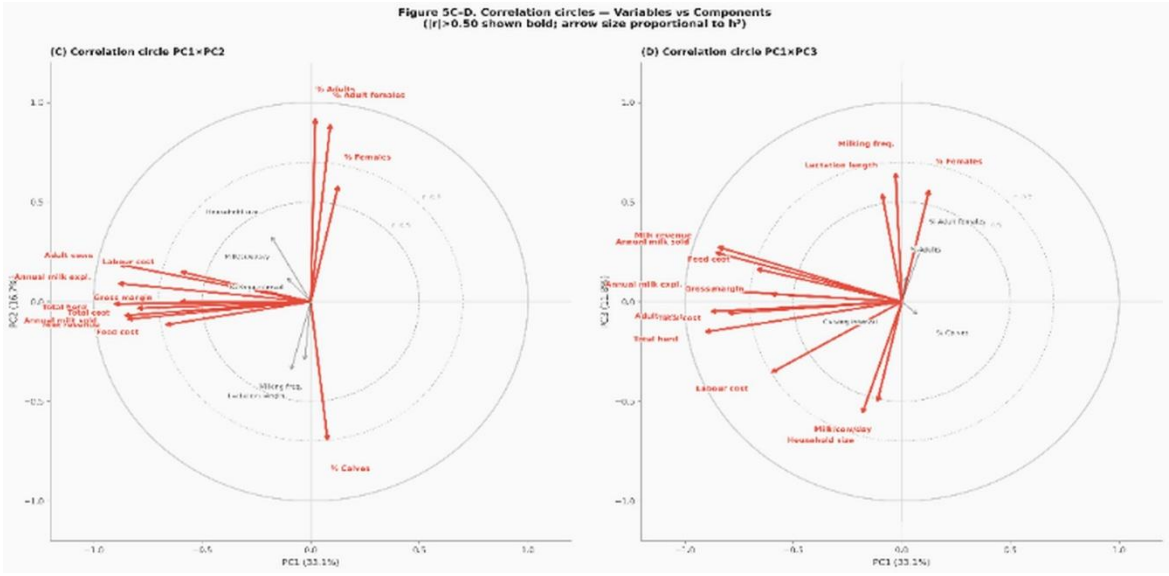


**Fig. 4. PCA loading structure for PC1-PC2 and PC1-PC3.**

## Exploratory farm configurations

Table 9 show the Ward clustering of the five retained component scores suggested three exploratory configurations. Type A included 12 large farms and was concentrated in Hodh Chargui; Type B included 20 intermediate farms; and Type C included 61 smaller farms with more frequent double milking and was more common in Brakna and Trarza. Separation was weak-to-modest (mean silhouette=0.258), and configuration membership remained associated with region ($\chi^2$=14.94, p=0.0048). Because 41% of surveyed farms were excluded and no participatory, bootstrap, or external validation was available, these groups are hypotheses for future sampling and co-design, not validated intervention or policy classes.

**Table 9. Descriptive characteristics and cautious use of the three exploratory Ward configurations**

| Profile | n | Dominant characteristics | Regional pattern | Use in this study |
|---|---|---|---|---|
| A | 12 | Large farms; high scale and economic intensity | Concentrated in Hodh Chargui | Hypothesis-generating large-farm configuration |
| B | 20 | Intermediate scale and mixed characteristics | Mixed regional membership | Hypothesis-generating intermediate configuration |
| C | 61 | Smaller farms; more frequent double milking | More common in Brakna and Trarza | Hypothesis-generating smaller-farm configuration |

Panel A shows the dendrogram and three-cluster cut; panel B shows configuration overlap in factor space. Ellipses are descriptive 95% data-concentration regions and should not be interpreted as inferential confidence regions (figure 5).

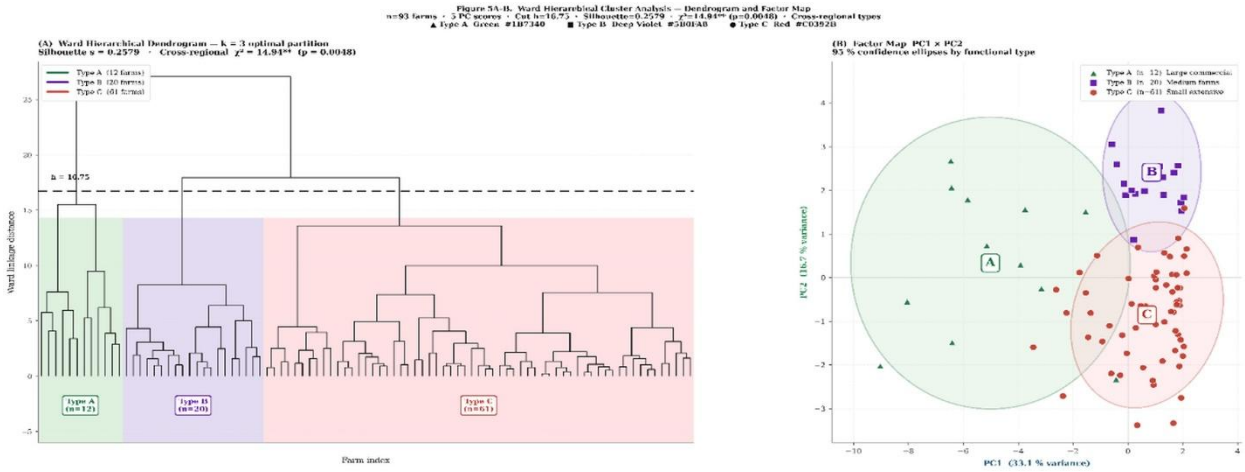

**Fig. 5. Exploratory Ward configurations and their position in the PC1-PC2 space.**
Panel A shows silhouette distributions (overall mean=0.258); panel B shows regional counts within each configuration ($\chi^2$=14.94, p=0.0048) (figure 6).

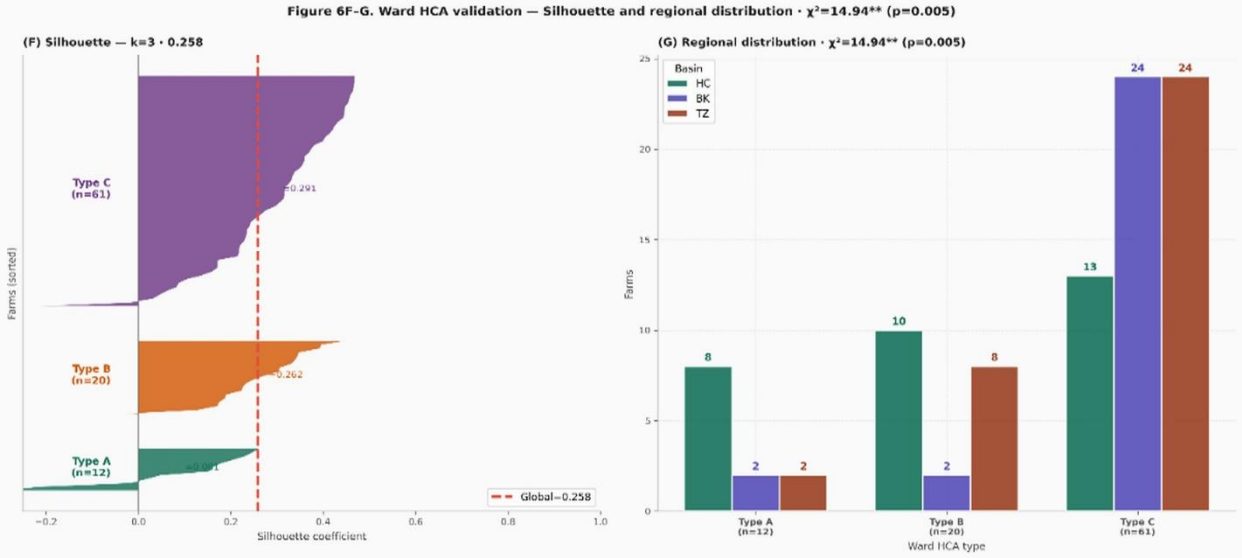


**Fig. 6. Internal cluster validation and regional composition.**

## Discussion

Viewed as agricultural systems, the surveyed farms were differentiated not by a single intensification gradient but by combinations of herd scale, demographic structure, milk management, expenditure, commercialization, and territorial connectivity. Four findings organize the interpretation: total milk volume was dominated by scale; commercialization followed a different combination of scale and feed expenditure; management practices were strongly patterned by territory; and multivariate configurations complemented, but did not replace, regional context. These findings constitute a diagnostic separation of system dimensions rather than evidence of causal pathways.

### Territory and farm configuration provide complementary information

Regional contrasts were pronounced for double milking, herd composition, inter-calving interval, lactation length, and selected expenditures, yet annual farm milk volume showed little regional separation. Adding regional indicators to the measured-factor model increased $R^2$ by only $\Delta R^2$=0.002. This does not demonstrate that territory acts through the measured farm variables, because mediation was not tested. It shows only that no large residual regional association was detected in this fitted sample. Region remains a proxy for opportunity and constraint structures: including water, feed markets, collection, processing, and services, that were incompletely measured. Similar work in East African dairy systems has shown that market and service connectivity can be more informative than broad rural-urban labels (van der Lee et al., 2020). This is consistent with evidence from northern Tanzania, where household-level cluster analysis captured substantial diversity in livestock production systems even within the same villages and administrative regions, indicating that quantitative farm-level classification is complementary to rather than redundant with territorial or administrative classification (de Glanville et al., 2020).

### Scale is not synonymous with intensification or efficiency

The near-unit coefficient of adult cow numbers in the milk-volume model is expected because farm output aggregates production across cows. This finding is consistent with evidence from the Malian dairy sector. In a nationally representative Cragg two-tiered model, herd size was identified as the strongest determinant of both market participation and milk-sales volume (Vroegindewey et al., 2021). Together, these results suggest that scale-driven market participation is a common characteristic of Sahelian dairy systems rather than a phenomenon specific to Mauritania. It identifies scale dependence, not biological efficiency or a causal benefit of herd expansion. Likewise, the positive feed-expenditure coefficient in the positive-revenue model may reflect feeding intensity, herd size, market integration, input prices, or reverse causation. Double milking was strongly patterned by region but was not statistically distinguishable from zero in the conditional revenue model. This apparent paradox may reflect several non-exclusive mechanisms: double milking may not translate into additional revenue when supplementary milk is consumed at the farm level or lost for lack of collection infrastructure; farms practicing double milking (predominantly smaller Type C farms in Brakna and Trarza) may face proportionally higher unit costs relative to marketed volume; and the conditional revenue model (M2) excludes zero-revenue farms, further limiting its ability to capture the full range of double-milking practices. Milking frequency can affect harvested milk and lactation

dynamics under adequate feeding and management, but the present design cannot estimate that causal effect (Stelwagen, 2001). These findings show why scale, input use, management, and market outcomes should be measured separately. Repeated indicators such as milk per lactating cow, feed use and cost per cow, marketed share, milk price, labor use, and margin per cow would be needed to evaluate technical and economic performance.

**From exploratory configurations to actionable typologies**

The multivariate analysis separated farm scale and economic magnitude from herd demography, management–commercialization, and reproductive dimensions. This supports the systems value of typologies for summarizing heterogeneity, but the observed components also reflect accounting and mathematical relationships among herd size, milk volume, costs, revenues, and margins. Previous work has emphasized that typologies become actionable only when their purpose is explicit, redundant variables are controlled, and categories are validated with intended users and new data (Cortez-Arriola et al., 2015; Toro-Mujica et al., 2020; Huber et al., 2024; Manners et al., 2025). Here, modest silhouette separation, exclusion of 65 farms, and continuing association with region mean that the three configurations should be treated as hypotheses for future sampling and extension dialogue, not as fixed national types.

**Implications for dairy-system transformation**

The findings argue against uniform interventions based only on region or herd size. A systems-oriented strategy would combine repeated farm and animal recording; feed and reproductive management adapted to the herd resource base; reliable milk collection, quality control, and market services; and extension that uses both territorial constraints and farm configuration. These are intervention hypotheses, not effects estimated by the present study. Box 2 separates what is directly supported from what still requires prospective evaluation.

**Box 2. From observed evidence to testable intervention hypotheses.**

| Observed evidence | Supported interpretation | Provisional intervention hypothesis | Evidence required |
|---|---|---|---|
| Near-unit adult-cow coefficient for total milk volume | Total volume is dominated by herd scale | Record lactating cows and express output per cow before promoting expansion | Repeated cow-level milk, lactation, and feed records |
| Strong regional contrast in double milking | Management practices are territorially patterned | Adapt extension to local feeding, labor, and collection conditions | Prospective comparison controlling for feed and herd composition |
| Feed expenditure associated with revenue among positive-revenue farms | Feed use and commercialization intensity covary | Coordinate feed planning with milk collection and price information | Two-part market-participation model and repeated prices/quantities |
| Three weakly separated configurations | Recurring combinations may guide future sampling | Use configurations for participatory discussion, not eligibility rules | Bootstrap (Hennig, 2007), participatory, and external validation |
| 41.8% zero or negative gross margin | High economic vulnerability, especially in subsistence-oriented farms | Target feed cost reduction and milk price stabilization for commercially active farms with negative margins | Longitudinal farm-level revenue and cost tracking with marketed share |

**Contribution and transferability**

The transferable contribution is a diagnostic framework for data-scarce pastoral and agro-pastoral dairy systems: scale, per-cow biological performance, management, commercialization, and territory should be measured as separate but connected dimensions. The framework can guide the design of sentinel-farm panels, stratified sampling, and participatory co-design in other settings where formal farm registers and longitudinal records are limited. It is directly applicable to analogous Sahelian contexts including agro-pastoral zebu systems in Mali, Niger, and Chad with adaptations for local herd mobility patterns, water availability cycles, and milk-market connectivity. Its transferability lies in the questions and indicators it prioritizes, not in the numerical coefficients or cluster labels reported for Mauritania.

**Limitations and research priorities**

The study is limited by non-probability chain-referral recruitment, possible dependence within referral networks, self-reported cross-sectional measurements, complete-positive selection in the log models, and complete-case selection in the configuration analysis. Important system variables were not measured consistently, including seasonal feed quantity and quality, labor time by task and sex, milk prices and marketed shares over time, travel time to collection points, herd mobility, land use, water availability, and environmental outcomes. Two additional gaps deserve explicit mention: (i) herd transhumance, a central feature of Mauritanian pastoral systems, was not systematically recorded;

seasonally mobile herds may generate substantially different production and revenue profiles from sedentary farms, and their exclusion or misclassification in the survey may bias system-level estimates; (ii) milk quality parameters (fat content, protein content, bacterial contamination) were not collected, yet they are key determinants of farm-gate price and market competitiveness. The M1 result is largely a scale decomposition; M2 does not model market participation; and the PCA includes accounting-related variables. Future research should use representative or well-characterized longitudinal panels, preserve recruitment-chain identifiers, estimate two-part commercialization models (Cragg, 1971), use repeated animal-level and price records, assess configuration stability through bootstrap resampling (Hennig, 2007), and validate typologies with farmers and service providers. Recent two-part market-participation models from West Africa reinforce this agenda: a double-hurdle analysis of smallholder crop markets in northern Ghana (Iddrisu et al., 2025) and a Cragg two-tiered model applied to the Malian dairy sector (Vroegindewey et al., 2021) both confirm that herd or farm scale is a leading determinant of market entry and sales intensity, consistent with the present findings. Such data would allow analysis of productivity, profitability, resilience, and trade-offs rather than static association.

## Conclusions

Moorish zebu dairy systems in Mauritania cannot be understood through farm size or regional location alone. Total milk volume was mainly scale-dependent, while commercialization reflected a different combination of herd size, feed expenditure, management, and market connection. Double milking and reproductive indicators were strongly patterned by territory, but annual milk volume varied more within than among regions. The exploratory farm configurations captured recurring combinations of dimensions but remained weakly separated and partly territorial. The study's main contribution is therefore diagnostic: it separates scale, biological performance, management, economics, and territory and translates them into a testable agenda for longitudinal recording and differentiated service design. National or causal recommendations require representative animal-level and farm-economic evidence.

The findings argue against uniform regional interventions: a systems-oriented strategy should combine repeated farm and animal recording, feed and reproductive management adapted to the local resource base, reliable milk collection and quality control infrastructure, and extension services that address both territorial constraints and farm-configuration diversity.

## Declarations


### Funding

This work was supported by the Office National de la Recherche et de Développement de l'Elevage et du Pastoralisme (ONARDEP) et l'Agence Nationale de la Recherche Scientifique et de l'Innovation (ANRSI), Mauritania.


### Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Individual contributions by the co-authors

Youssouf El Hadj: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing - original draft. Mohamed Ould Ahmed: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Supervision, Validation, Writing - original draft, Writing - review and editing. Abir Hamrouni: Formal analysis, Writing - review and editing. Sidi Hamady: Data curation, Writing - review and editing. Derradji Harek.: Formal analysis, Writing-review and editing. M'Naouer Djemali: Supervision, Validation, Writing - review and editing. Ali Ould Mohamed Salem Boukhary: Supervision, Validation, Writing - review and editing.

### Data availability

The de-identified analytical dataset, data dictionary, and analysis code are available from the corresponding author upon reasonable request, subject to confidentiality restrictions protecting participating farms.

### Statement of Animal Rights

The study involved interviews with adult owners or managers of Moorish zebu dairy farms, and no experimental procedures were performed on animals. This study was approved by the Research Ethics Committee of the University of Nouakchott 2022/2023. Verbal, rather than written, consent was considered appropriate given the non-sensitive, minimal-risk nature of the information collected (herd demographic data, farm management practices, and aggregated economic data, ...). This verbal consent was recorded by a note signed by the interviewer on the survey form, attesting that consent was given orally by the respondent.

### Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used Claude (Anthropic) and ChatGPT (OpenAI) to assist with translation, language editing, organization, and formatting. After using these tools and services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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