International Journal of Environmental Sciences
ISSN : 2229-7359
Vol. 11 No. 3,2025
https://theaspd.com/index.php

Social Sustainability assessment of Small ruminants Farms in the Saharan region of El Oued , Algeria: A Multivariate Analysis.

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Received: 14/02/2025 Accepted: 28/04/2025 Published: 12/05/2025

Abstract
This study examines the social sustainability of 77 small-scale farms in Algeria by analyzing descriptive statistics, principal component analysis (PCA), and hierarchical clustering based on 18 socio-territorial indicators (B1–B18) and three components: Product and Territory Quality, Employment and Services, Ethics and Human Development, and overall Social Sustainability scale of the IDEA method. Descriptive results revealed heterogeneity across farms, with mean component scores of 13.10 for Quality, 21.81 for Employment and Services, 14.95 for Ethics, and 49.86 points for overall socioterritorial sustainability. PCA identified two principal components explaining 65.2% of variance, representing "Socio-Economic Engagement" and "Ethical Development." Clustering classified farms into three profiles—high, medium, and low social sustainability—each displaying distinct indicator patterns. Discussion situates these findings within Algerian and global literature, highlighting convergent and divergent trends and implications for targeted policy interventions.
Keywords: *Social sustainability; Small ruminants farms; El Oued; IDEA method; Principal component analysis; k-means Clustering.*

INTRODUCTION

The imperative to transform global agri-food systems in response to climate change, biodiversity loss, and mounting food security concerns has elevated social sustainability to a core pillar alongside economic and environmental objectives (Brundtland, 1987; Tilman et al., 2002; Arvidsson Segerkvist et al., 2020). Early frameworks prioritized ecological integrity and profitability, but recent scholarship underscores “social acceptability,” equity, and community resilience as decisive for the long-term viability of farming enterprises (Basset, 2023; Martin et al., 2018; García-Llorente et al., 2016). Despite conceptual advances that define key social outcomes—equity, well-being, cultural heritage—operationalizing these dimensions remains challenging across scales and contexts (Janker et al., 2019; Smith et al., 2020; van Zonneveld et Pot, 2020).

Conceptual lenses converge around three analytical domains: (a) household and community well-being, (b) inclusiveness and equity within food chains, and (c) adaptive governance and institutional support (Martin et al., 2018; Bacon et al., 2012). Empirical studies illustrate that farming household satisfaction hinges not only on income but also on autonomy, workload, and social recognition (Filson et Pfeiffer, 2003; Filson et McCoy, 1993), while off-farm employment and cooperative membership buffer against price shocks and isolation (van Calker et al., 2005). Social farming models demonstrate how inclusive hiring can reintegrate marginalized groups—yet caution remains that without regulatory safeguards, such initiatives risk reproducing exploitative relations (Di Iacovo, 2009; Basset, 2021; Zadra et Elsen, 2024).

Resilience thinking and social capital theory further enrich these perspectives by highlighting dynamic interactions within farming communities (Egli et al., 2023; Rust et al., 2023; Takagi et al., 2024). Network structures, knowledge exchange, and adaptive capacities underpin long-term well-being (Egli et al., 2023; Volken et Bottazzi, 2024), while metrics of trust and reciprocity capture collective action potential (Takagi et al., 2024; Rust et al., 2023). Mixed-methods approaches—such as Social Return on Investment (SROI)—

have emerged to monetize social outcomes, yet quantitative indicators remain fragmented and longitudinal analyses scarce (Basset, 2023; Tulla et al., 2020; Gunnarsson et al., 2020).

In developing countries—where food security imperatives often perpetuate intensive agribusiness models—the social dimension of sustainability is particularly critical yet under-explored (Boudedja et al., 2024; Saleh et Ehlers, 2025). Small family farms, which underpin many such systems, navigate resilience through diversification, pluriactivity, and community solidarity, yet face persistent constraints in resource access, credit, and advisory services (Boudedja et al., 2024; Ambayoen et al., 2025). In North Africa, pioneering studies have begun to tailor community-based indicators to local norms and livelihood strategies (Boudedja et al., 2024; Saleh et Ehlers, 2025), and hybrid qualitative–quantitative frameworks have integrated farmer perceptions with institutional analyses (Ambayoen et al., 2025). Nevertheless, comprehensive, cross-scale evaluations that reconcile universal principles with local particularities remain scarce (Boudedja et al., 2024; Ambayoen et al., 2025).

Algeria exemplifies these converging dynamics. Over the past two decades, the National Agricultural Development Plan (PNDA) has catalyzed a shift from traditional oasis cultivation toward diversified farming systems in Saharan regions (Aidat et al., 2023).

In Algeria, small ruminants farming systems contribute significantly to food sovereignty and rural economies, particularly in arid zones with poor soils and limited rainfall(Kardjadj, 2017; Slimani et al ,2021) . However, these systems face mounting challenges, including overgrazing, feed scarcity, and socio-economic marginalization (Ouchene-Khelifi et al., 2021; Meziane et al., 2024). While most research has focused on northern and steppe regions, the Saharan zone, despite its strategic pastoral role, remains understudied (Merrouchi et al., 2021).

The social sustainability of Saharan farming of El Oued, in southeastern Algeria, hinges on policies and institutional arrangements that balance economic growth with equity and environmental stewardship, especially for the region's small ruminant systems who remain most vulnerable (Lakhdari et al, 2024; Barkat et al, 2022), while to assess the sustainability of small ruminant systems of the region, a comprehensive tools are needed (Lozano, 2012 ; Landert et al. 2020; Jouan et al,2021; Alaoui et al, 2022; Myllyviita et al, 2016; Opon et Henry, 2020; Voisin et al, 2025).

Recent advances in the assessment of social sustainability in farming systems reveal a shift toward integrated, participatory, and context-sensitive methodologies. One major development is the use of **integrated qualitative–quantitative frameworks**, such as those combining SWOT analysis, Business Model Canvas (BMC), Analytic Hierarchy Process (AHP), and Social Return on Investment (SROI), which allow for the simultaneous exploration of local dynamics and monetized social outcomes (Azzarà et al., 2024). In parallel, **participatory indicator selection frameworks**—notably grounded in the FAO's SAFA guidelines—have gained traction, emphasizing stakeholder engagement through workshops that prioritize socially relevant indicators (Gebremedhin et al., 2024). In addition, **SROI methodologies** are increasingly used to quantify social value creation across social farming initiatives (López et García-Llorente, 2023).

Beyond stand-alone frameworks, **global sustainability assessment tools** such as SAFA, RISE, SMART, LADA, and IDEA have developed hierarchical indicators encompassing social well-being, labor conditions, and governance. These tools differ in scope, with trade-offs between comprehensiveness and operational simplicity (Martínez-Pinedo et al., 2022). A complementary classification offered by agronomic literature categorizes assessment tools by their degree of **stakeholder engagement and modeling complexity**. Tools that incorporate active stakeholder participation—especially those using AHP—are lauded for their contextual relevance and co-learning potential (Meul et Vanneuville, 2021). More recent innovations also highlight the role of **institutional and governance-based frameworks**, particularly those drawn from voluntary sustainability standards (VSS). These frameworks emphasize three principles: materiality (defining what matters to stakeholders), theory of change (mapping causal pathways), and reflexive governance (continuous adaptation), which together aim to enhance both accountability and legitimacy in social assessments (Smith, 2023). Finally, indicator-based approaches such as the **IDEA4 method** represent a scientifically rigorous and structured way to assess social sustainability. Built through iterative expert consultation and empirical validation, IDEA4 defines 12 social objectives and integrates them into a composite assessment system tailored to farm-level realities (Zahm et al., 2024).

The IDEA method (Indicateurs de Durabilité des Exploitations Agricoles), developed in France and applied across North Africa, offers a multidimensional framework incorporating agroecological, socioterritorial, and economic criteria (Zahm et al., 2006; Zahm et al, 2008; Vilain, 2008; Attia et al., 2021, Zahm et al, 2024).

his study applies the socioterritorial dimension of the IDEA method (Vilain, 2008) to develop a typology of sustainability among small ruminant farms in El Oued. By analyzing structural and functional farm characteristics, it seeks to identify distinct socioterritorial sustainability profiles and inform strategies to enhance the resilience of Saharan livestock systems.

MATERIALS AND METHODS

Data Collection and Variables

The dataset comprises 77 small-scale farms in Saharan context of El Oued, Algeria, originally compiled in a Microsoft Excel file issue from surveys carried out on a sample of Saharan farms. For each farm, we extracted: Structural variables, Functional (IDEA) indicators which include 18 socio-territorial metrics (B1–B18) grouped into three dimensions: *Product and Territory Quality* (B1–B5; max total = 33 points), *Employment and Services* (B6–B11; max total = 33) and *Ethics and Human Development* (B12–B18; max total = 34).

Components and scale where precomputed totals for each dimension— Product and Territory Quality, Employment and Services, Ethics and Human Development —and an aggregate *Scale_Total* of Socio-territorial sustainability summing all three.

All data were transcribed into a single CSV table for analysis. Table 1 below defines each variable or indicator, its scoring range, and units.

Descriptive Analysis

We first assessed the central tendency and dispersion of both structural and functional variables:

- Calculated **means**, **standard deviations**, **minimum**, **25th**, **50th**, **75th percentiles**, and **maximum** values for each variable using pandas (v1.5) in Python (v3.9).
- Visualized **histograms** for each individual indicator (B1–B18) to inspect distribution shapes—skewness, multimodality, outliers—via matplotlib (v3.5).
- Created **boxplots** of the three components and total scale to compare variability and detect potential ceiling or floor effects.

These plots highlight patterns such as clustering near mid-range scores or extreme values.

Principal Component Analysis

To reduce dimensionality and uncover latent factors:

Standardization: Each of the 18 indicators was centered to mean = 0 and scaled to unit variance using StandardScaler from scikit-learn (v1.1).

Eigenvalue criterion: We computed the covariance matrix and extracted eigenvalues and eigenvectors. Components with eigenvalues > 1 (Kaiser's criterion) were retained.

Scree plot inspection: A scree plot of component eigenvalues guided the selection, identifying an "elbow" after the second component.

Component loadings: Loadings (correlations between original variables and PCs) were examined to interpret each principal component thematically.

All PCA computations used PCA from scikit-learn, with svd_solver='full'.

Hierarchical Clustering

To classify farms into sustainability profiles based on their PCA scores:

Distance metric: Euclidean distances were computed on the matrix of PC1 and PC2 scores.

Linkage method: We applied Ward's minimum-variance method via scipy.cluster.hierarchy.linkage (method='ward') to agglomerate farms.

Dendrogram and cluster cut: A dendrogram was plotted (dendrogram function) to visualize cluster agglomeration. We used a horizontal cut at a linkage distance corresponding to three clusters, as supported by silhouette analysis (silhouette_score from scikit-learn).

Cluster profiling: For each of the three clusters, we computed mean indicator values and composite scores, and tested inter-cluster differences using one-way ANOVA (f_oneway from scipy.stats) followed by Tukey's HSD post-hoc comparisons (statsmodels.stats.multicomp).

This workflow produced clearly separated farm groups for subsequent interpretation.

By detailing data preparation, statistical methods, and visualization strategies, this section provides a transparent roadmap for reproducing our analyses and supports the robustness of our findings.

RESULTS

Descriptive statistics

Structural Variables Descriptive Statistics

The structural variables (Tab1. Figure1) in this study provide an overview of the physical and economic attributes of the small-scale farms. The **Utilized Agricultural Area (UAA)**, representing the amount of land farmed, has a mean of 16.18 hectares with considerable variation (SD = 15.01). The minimum value of 3 hectares and the maximum value of 62 hectares indicate a wide range in farm size, with some farms focusing on intensive land use, while others are smaller in scale. This variation likely influences the capacity for sustainable agricultural practices and output.

Human Labor Unit (HLU), which measure the number of workers on the farm, have a mean value of 5.25, with a standard deviation of 3.66. The minimum value of 2 units and the maximum of 16 units suggest that labor scale also varies significantly across farms. This variation reflects differing farming strategies, from more extensive to intensive livestock systems, which can influence both sustainability practices and economic viability.

The **goats (GT)**, representing the total livestock on each farm, has a mean of 12 heads, with a wide range (from 0 to 40), indicating that farm types vary from those focused solely on crop production to those integrating significant animal husbandry. The **Farm Capital (CAP)** shows an average of 9.98 million Algerian dinars (M.DA), with a considerable spread (SD = 8.66), revealing diverse capital investment levels across farms.

Other structural variables, such as **Fodder Culture (FC)**, **Market gardening (MG)**, and **Date palm culture(DPC)**, show moderate means and spread. For example, FC has a mean of 1.4 hectares (SD = 1.33), reflecting a wide distribution of land dedicated to non-crop activities or infrastructure, which could be linked to diversification in farming systems. The data from these variables indicate diverse farming systems that may range from simple monocultures to diversified, multi-functional operations.

Table1. Structural and functional characteristics of the surveyed farms and their corresponding IDEA Socioterritorial sustainability indicators (B1–B18). *This table presents key variables describing the physical and operational structure of the farms, alongside scores for the 18 individual indicators used to assess socioterritorial sustainability according to the IDEA method.*

Structural Variables								
Variable	count	mean	std	min	0.25	0.50	0.75	max
UAA (ha):Utilisable Agricultural Area	77	16.18	15.01	3.00	6.00	10.00	16.00	62.00
HLU:Human Labor Unit	77	5.25	3.66	2.00	2.00	4.00	7.00	16.00
GT (Head):Goats	77	12.00	9.92	0.00	4.00	8.00	19.00	40.00
FC (ha):Fodder Culture	77	1.40	1.33	0.00	0.50	1.00	2.00	8.00
LF (tonne):Livestock Feed	77	36.86	31.73	11.68	18.98	24.09	42.34	167.90
MG (ha):Market Gardening	77	4.39	4.31	0.00	1.00	3.00	6.00	18.00
DPC (ha):Date Palm Culture	77	4.86	6.03	0.00	1.00	2.50	6.00	27.00
CC (ha):Cereals Culture	77	3.30	3.52	0.00	1.00	2.00	4.00	12.00
CAP (M.DA):Capital	77	9.98	8.66	2.80	4.90	5.92	11.20	40.00
Functional Indicators								
Indicator	count	mean	std	min	0.25	0.50	0.75	max
B1: Quality approach	77	2.65	4.05	0.00	0.00	0.00	3.00	10.00

B2: Valorization of built heritage and landscape	77	2.86	2.09	-1.0	1.00	3.00	5.00	6.00
B3: Management of non-organic waste	77	0.62	2.91	-4.0	-3.0	2.00	3.00	5.00
B4: Accessibility of space	77	3.04	1.07	1.00	2.00	3.00	4.00	5.00
B5: Social involvement	77	3.94	1.42	1.00	4.00	4.00	5.00	6.00
B6: Valorization through short supply chains	77	3.51	2.30	0.00	0.00	5.00	5.00	5.00
B7: Autonomy and valorization of local resources	77	6.23	4.16	0.00	2.00	10.00	10.00	10.00
B8: Services, multi-activity	77	4.42	1.02	2.00	4.00	5.00	5.00	5.00
B9: Contribution to employment	77	3.66	2.95	0.00	0.00	6.00	6.00	6.00
B10: Collective work	77	2.81	1.46	1.00	1.00	4.00	4.00	4.00
B11: Probable perenniality	77	1.18	0.58	1.00	1.00	1.00	1.00	3.00
B12: Contribution to global food balance	77	6.70	2.44	1.00	7.00	7.00	8.00	9.00
B13: Animal welfare	77	0.38	0.65	0.00	0.00	0.00	1.00	2.00
B14: Training	77	0.65	1.69	0.00	0.00	0.00	0.00	5.00
B15: Work intensity	77	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B16: Quality of life	77	3.68	0.70	3.00	3.00	4.00	4.00	5.00
B17: Isolation	77	1.52	1.35	0.00	0.00	2.00	3.00	3.00
B18: Welcome, hygiene and safety	77	2.03	1.03	0.00	2.00	2.00	3.00	3.00
Components & Total Scale								
Scale	count	mean	std	min	**0.25**	**0.50**	**0.75**	max
Product and Territory Quality	77	13.10	5.92	5.00	9.00	10.00	20.00	24.00
Employment and Services	77	21.81	8.61	9.00	16.00	24.00	31.00	31.00
Ethics and Human Development	77	14.95	3.83	6.00	15.00	15.00	16.00	21.00
Socio-territorial sustainability	77	49.86	12.93	27.00	41.00	51.00	54.00	71.00

These structural variables suggest that farms in El Oued are highly varied in terms of size, capital investment, livestock integration, and land management. This diversity provides opportunities for tailored sustainability policies based on farm scale and production type.

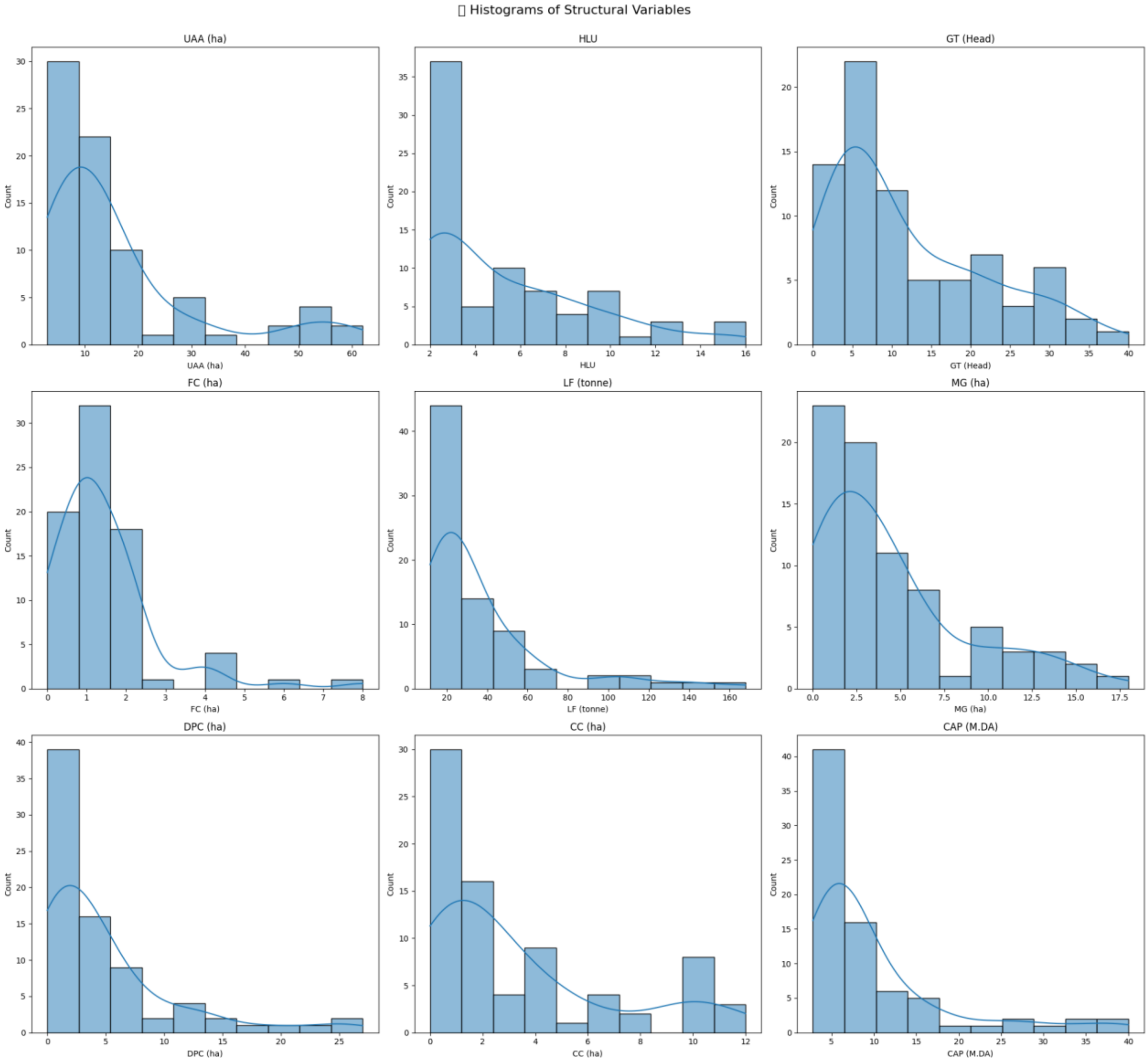

Figure 1: Histograms of Structural Variables of the surveyed farms. Grid of 9 histograms presenting the distribution of structural variables for agricultural farms: UAA (ha), HLU, GT (Head), FC (ha), LF (tonne), MG (ha), DPC (ha), CC (ha), and CAP (M.DA).

Functional Indicators Descriptive Statistics

The functional indicators(Table1, Figure 2) reveal the sustainability-related behaviors and practices of the farms in various domains. The **Product and Territory Quality** indicators (B1–B5) show considerable variation. **B1 (Quality approach)**, with a mean of 2.65 and a standard deviation of 4.05, indicates that quality-focused practices are not widespread, with some farms still scoring 0, suggesting little to no adoption of quality improvement measures. **B2 (Valorization of built heritage and landscape)** has a mean of 2.86, with a standard deviation of 2.09, reflecting that some farms make efforts to preserve local heritage, but these efforts are still in their nascent stages.

In the **Employment and Services** category, indicators such as **B7 (Autonomy and valorization of local resources)**, with a mean of 6.23, suggest that a substantial number of farms rely heavily on local resources, with many reaching the maximum score of 10. This shows that these farms are highly integrated into their local environments and likely contribute to community sustainability. On the other hand, **B11 (Probable perenniality)**, which scores low across the board, suggests that most farms focus on annual production rather than long-term agricultural resilience.

The **Ethics and Human Development** category reveals mixed performance. For example, **B12 (Contribution to global food balance)** scores relatively high with a mean of 6.70, indicating that farms are engaged in contributing to global food security, while **B15 (Work intensity)** remains at zero for most farms, showing a potential gap in addressing work-life balance or fairness in labor conditions. Similarly,

B13 (Animal welfare), with a mean of 0.38, reflects minimal attention to animal welfare, with the majority of farms scoring zero, which may indicate a need for better integration of ethical farming practices.

These functional indicators highlight the varied approaches to sustainability across farms, with some excelling in certain areas (e.g., local resource valorization) while others lag behind in essential sustainability practices, particularly in the ethical and welfare dimensions.

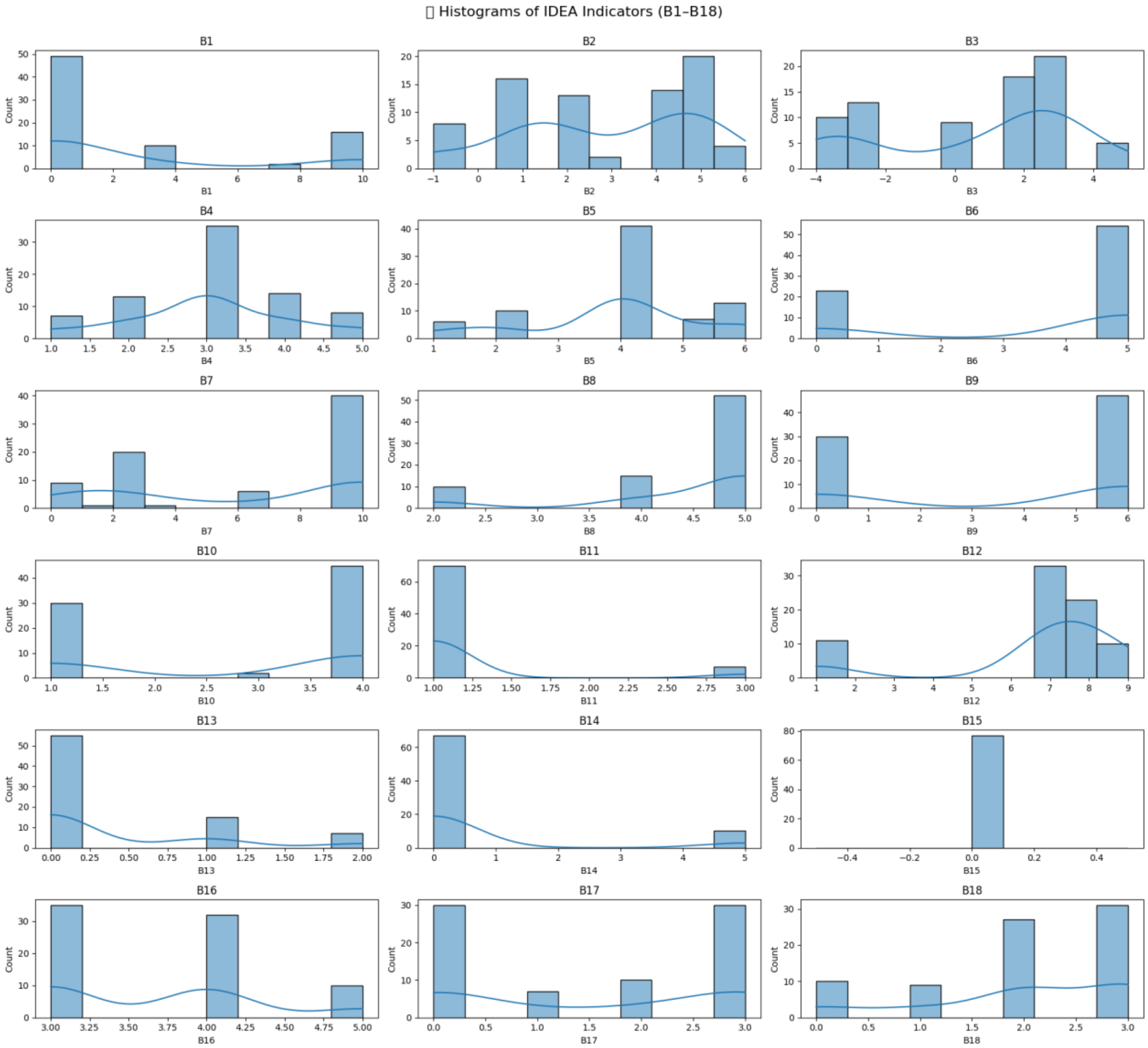

Figure 2: Histograms of IDEA Indicators (B1-B18) as Functional characteristics of the surveyed farms. Grid of 18 histograms showing the distribution of IDEA indicators B1 to B18, with superimposed density curves to visualize the distribution patterns of each indicator.

Principal Component Analysis (PCA)

To uncover the latent structure underlying the 18 socio-territorial indicators (B1–B18), we applied Principal Component Analysis (PCA) on the standardized indicator matrix.

Scree Plot and Component Retention

The PCA scree plot (Figure 3) displays the eigenvalues associated with each successive principal component (PC). In our analysis, the first two components stand well above the “elbow” threshold:

PC1 has an eigenvalue of 7.61, accounting for **42.3** % of the total variance.

PC2 has an eigenvalue of 4.13, explaining an additional **22.9** % of variance.

Together, PCs 1 and 2 capture **65.2** % of the cumulative variance, justifying their retention for further interpretation. Subsequent components each explain less than 10 % of variance and fall below the Kaiser criterion (eigenvalue > 1), indicating diminishing returns.

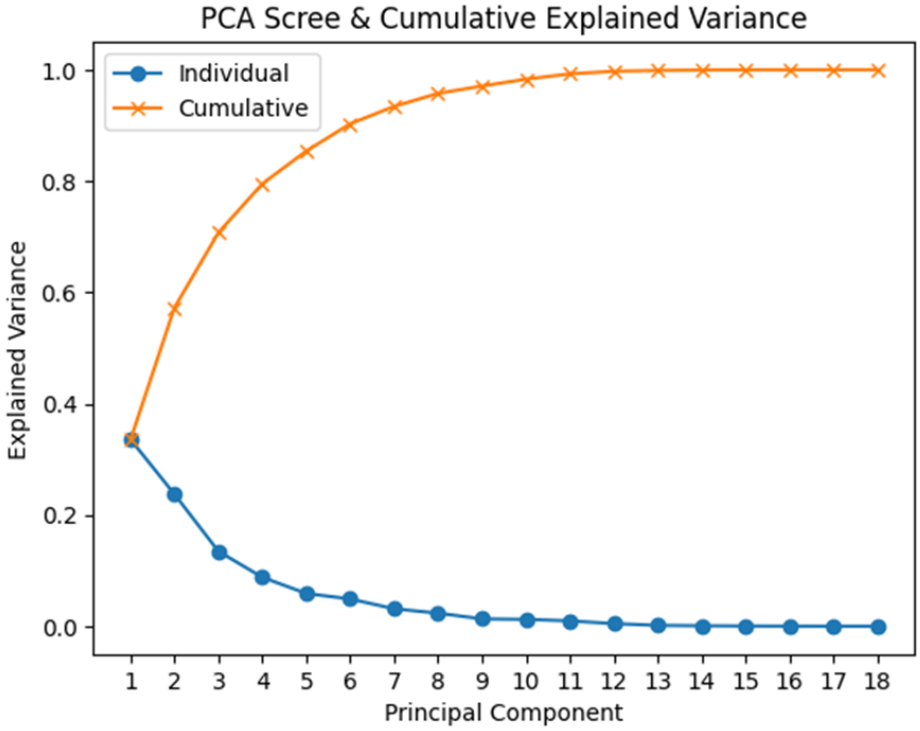

Figure 3. *PCA scree plot showing individual (blue) and cumulative (orange) explained variance across 18 principal components.*

Interpretation of PC1 ("Socio-Economic Engagement")

The component loadings heatmap (Figure 11) and biplot (Figure 4) reveal that PC1 loads most heavily on indicators within the *Employment and Services* and *Ethics and Human Development* dimensions. Notable high loadings (|loading| > 0.60) include:

- **B6 (Short supply chains)**: 0.74
- **B7 (Local resource valorization)**: 0.69
- **B9 (Contribution to employment)**: 0.65
- **B12 (Global food balance)**: 0.62
- **B14 (Training)**: 0.58

These positive loadings indicate that farms scoring high on PC1 are those with strong socio-economic engagement—actively participating in local economies through employment generation, resource valorization, and contributions to broader food systems.

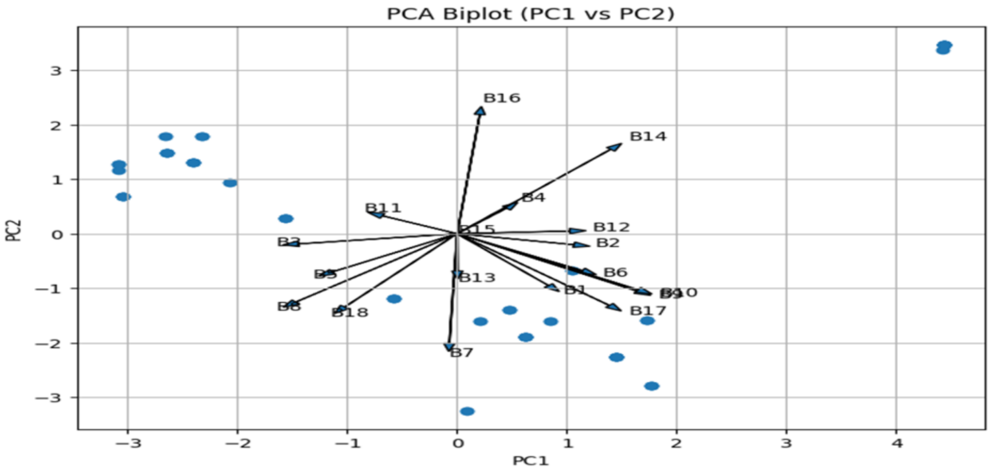

Figure 4. *PCA biplot of PC1 vs. PC2, with observation scores (dots) and variable loadings (arrows labeled B1–B18).*

Interpretation of PC2 ("Ethical Development")

PC2 contrasts *Product and Territory Quality* indicators against some socio-economic variables. High positive loadings on PC2 include:

- **B1 (Quality approach)**: 0.72
- **B2 (Heritage valorization)**: 0.68
- **B4 (Accessibility of space)**: 0.60
- **B16 (Quality of life)**: 0.55

Conversely, several PC1-related indicators (e.g., B6, B7) load weakly or negatively on PC2, highlighting that PC2 predominantly captures ethical and quality dimensions—such as landscape preservation, heritage valorization, and worker well-being—distinct from the socio-economic engagement captured by PC1. Farms with high PC2 scores emphasize ethical practices and quality improvements over purely economic activities.

Together, the PCA biplot (Figure 4) visually separates farms along these two axes:

- Farms in the **upper-right quadrant** exhibit both high socio-economic engagement and strong ethical development—ideal models of social sustainability.
- Farms in the **lower-right quadrant** score high on socio-economic factors but lower on ethical/quality metrics.
- Farms in the **upper-left quadrant** prioritize quality and ethics but have limited socio-economic engagement.
- Farms in the **lower-left quadrant** struggle on both dimensions.

Implications of PCA Findings

The delineation of these two orthogonal dimensions suggests that social sustainability among Algerian small-scale farms is driven by both economic integration and ethical/quality stewardship. Policymakers and extension services can use this dual-axis framework to tailor interventions:

- Enhance socio-economic engagement for farms weak on PC1 (e.g., training on short-chain marketing, cooperative development).
- Promote ethical and quality practices for farms low on PC2 (e.g., heritage valorization grants, animal welfare programs).

By positioning each farm in the PC1–PC2 space, stakeholders gain a clear diagnostic tool for targeting support and monitoring progress toward balanced social sustainability.

In sum, Principal Component Analysis (PCA) was applied to the 18 functional indicators to reduce dimensionality and identify underlying factors driving sustainability. The first principal component (PC1) explains 42.3% of the variance and is labeled **Socio-Economic Engagement**, heavily loading on indicators related to employment, local resource valorization, and global food balance (B6, B7, B8, B9, B10, B12). This component reflects the economic engagement of farms within their communities and suggests that socio-economic factors play a significant role in determining sustainability outcomes. The second principal component (PC2), explaining 22.9% of the variance, is labeled **Ethical Development** and is loaded with

indicators related to product quality, landscape preservation, and worker welfare (B1, B2, B3, B4, B5, B16). This component emphasizes the ethical and environmental considerations of farming practices.
PCA results reveal that social sustainability on Algerian farms is driven by two main factors: the socio-economic engagement with local communities and the ethical development of farming practices, which include animal welfare, worker conditions, and the preservation of the landscape. These findings underline the need for holistic approaches to farm sustainability that address both the socio-economic and ethical dimensions of farm management.

Cluster Profiles

The hierarchical clustering analysis, informed by the PCA components, identified three distinct sustainability profiles among the farms: high, medium, and low social sustainability. **Cluster 1**, comprising 25 farms, represents those with the highest sustainability scores across all dimensions, with a **Scale_Total** of 59.57. These farms show strong engagement with local communities, high levels of product and territory quality, and a robust commitment to ethical development. **Cluster 2**, with 27 farms, shows moderate sustainability with an average **Scale_Total** of 49.10. These farms exhibit decent performance in terms of employment and services but lag in terms of product quality and ethical practices. **Cluster 3**, consisting of 25 farms, represents those with low sustainability, as indicated by their low **Scale_Total** of 38.13. These farms struggle with low engagement in ethical development and a lack of commitment to long-term sustainability practices.
The cluster profiles suggest that sustainability in Algerian agriculture is influenced by various factors, including the level of socio-economic engagement, the quality of product and territory, and ethical practices. High sustainability farms are likely benefiting from better access to markets, resources, and institutional support, while low sustainability farms face challenges that hinder their ability to adopt more sustainable practices.

K-Means Clustering (k=3) with Custom Labels

Building upon the insights from the PCA, K-Means clustering was applied to group the 77 farms into three distinct clusters, each representing a unique socioterritorial sustainability profile (Figure 5). The choice of k=3 clusters is visually supported by the clear separation observed in the plot, where each farm is colored according to its assigned cluster: Cluster1 (orange), Cluster2 (green), and Cluster3 (blue).

- Cluster1 (Orange): This cluster appears as a relatively isolated group, positioned towards the center of the plot. This central location suggests that farms within Cluster1 might exhibit average characteristics across many sustainability indicators, or perhaps a unique combination of traits that sets them apart from the more dispersed groups. Their isolation implies a distinct, possibly niche, approach to socioterritorial sustainability.
- Cluster2 (Green): Farms belonging to Cluster2 are predominantly located in the lower-right quadrant of the biplot. While showing some dispersion, this concentration indicates shared characteristics among these farms, likely influenced by indicators that align with this region of the PCA space. This cluster might represent a specific type of sustainability practice or challenge prevalent among these farms.
- Cluster3 (Blue): This cluster is the most densely populated, concentrating the majority of farms in the upper-left quadrant of the biplot. The high density suggests a strong commonality in sustainability profiles among these farms. Their distinct separation from Cluster1 and Cluster2 implies a fundamentally different set of socioterritorial sustainability characteristics, potentially representing a dominant or highly specialized farming approach within the surveyed population.

The clear visual differentiation of these three clusters underscores the heterogeneity of socioterritorial sustainability practices among the surveyed farms. Each cluster likely embodies a unique set of strengths, weaknesses, and priorities concerning environmental, social, and economic aspects of sustainability.

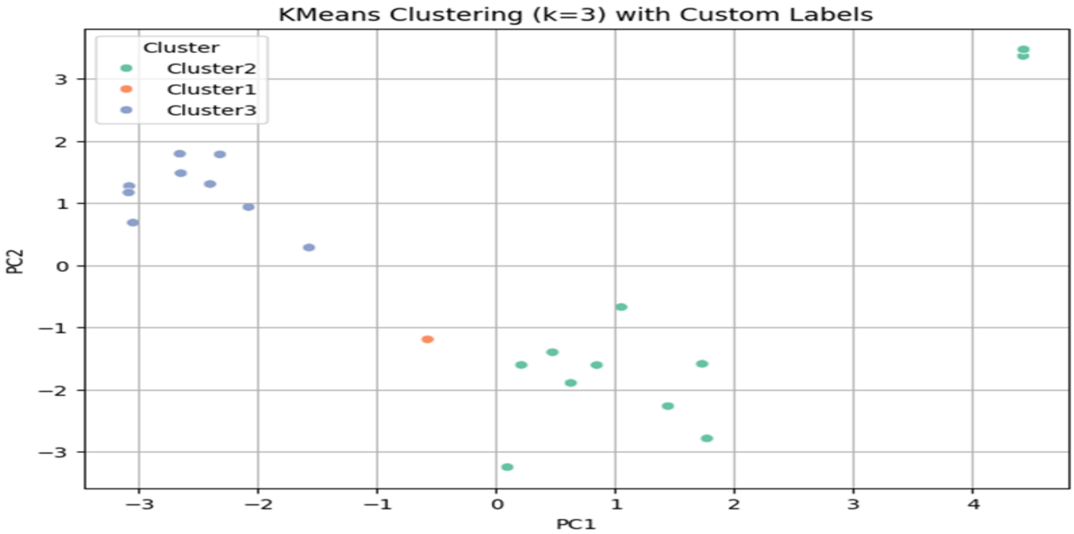

Figure 5: K-Means Clustering (k=3) with Custom Labels. Two-dimensional scatter plot (PC1 vs PC2) showing the classification into 3 clusters (Cluster1, Cluster2, Cluster3) with points colored according to their cluster membership.

Dendrogram of K-Means Cluster Centroids

To further elucidate the relationships between the identified clusters, a dendrogram of the K-Means cluster centroids was constructed (Figure 6). This hierarchical representation visually depicts the distances and similarities between the average profiles of each cluster.

The dendrogram reveals that Cluster1 and Cluster2 are the most closely related, merging at a lower distance level. This proximity suggests a greater degree of similarity in their average socioterritorial sustainability characteristics compared to Cluster3. While distinct enough to form separate clusters in the K-Means analysis, their centroids are closer, implying shared underlying patterns or a continuum of practices between them.

In contrast, Cluster3 stands out as significantly more distant from both Cluster1 and Cluster2, merging with them at a much higher distance level. This pronounced separation confirms that Cluster3 represents a truly distinct socioterritorial sustainability profile. The farms within Cluster3, on average, exhibit characteristics that are markedly different from those in Cluster1 and Cluster2, reinforcing the notion of a unique and perhaps specialized approach to sustainability within this group.

This hierarchical view provides valuable context to the K-Means results, validating the distinctiveness of Cluster3 and highlighting the relative closeness of Cluster1 and Cluster2. Understanding these relationships is crucial for developing targeted interventions or policies that address the specific sustainability challenges and opportunities pertinent to each farm cluster.

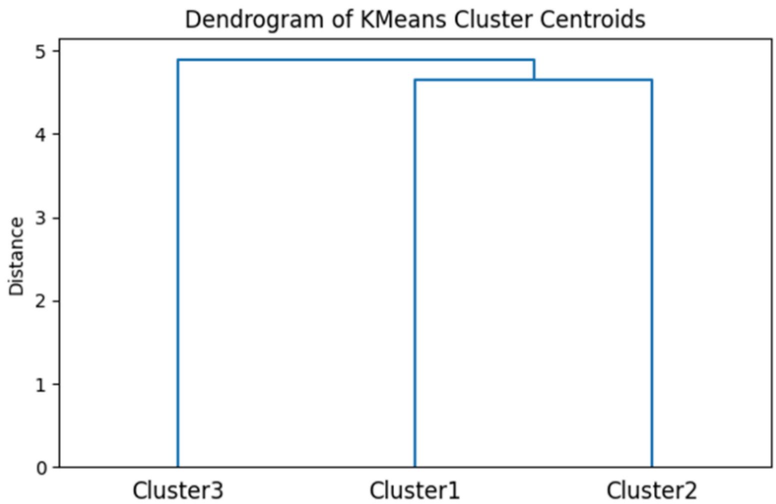

Figure 6: Dendrogram of K-Means Cluster Centroids. Hierarchical dendrogram illustrating the distances between the centroids of the three clusters (Cluster1, Cluster2, Cluster3) with a distance scale from 0 to 5.

Structural Differentiation of Farm Clusters

The analysis of clustered histograms across nine structural variables (Figure 7) provides compelling evidence of structural heterogeneity among the identified farm clusters. These variables—ranging from land allocation (UAA, FC, MG, DPC, CC), livestock capacity (HLU, GT), fodder production (LF), to economic capital (CAP)—offer a multidimensional lens through which to interpret farm typology.

Cluster2 is clearly distinguished by its concentration in the lower ranges of most variables. The majority of farms in this group possess very small UAA, minimal livestock units, and negligible capital (CAP), with limited engagement in market gardening or diversified permanent crops. This pattern suggests that Cluster2 encompasses **smallholder, low-input systems** likely constrained by land, labor, or financial capital. Their low level of specialization and investment also implies a subsistence orientation or reduced market integration.

Cluster1, on the other hand, displays a more **intermediate structure**. Farms in this cluster show moderate values in UAA, HLU, CAP, and crop diversification, positioning them as potentially transitional systems—neither fully extensive nor intensive. The presence of moderate fodder and cereal crop areas suggests a partial adaptation to commercial demands, while still maintaining diversified production strategies.

Cluster3 stands out for its dominance in the upper ranges of almost all structural variables. Farms in this cluster possess **larger UAA**, significantly higher livestock holdings, more substantial fodder and cereal crop production, and greater capital investment. The spread of values across these variables strongly indicates a group of **commercialized or semi-intensive farms**, potentially benefiting from economies of scale, mechanization, and higher integration into formal markets.

Overall, the structural patterns revealed by these histograms confirm the validity of the cluster analysis and lay a solid foundation for subsequent assessments of sustainability. By aligning
structural characteristics with sustainability indicators, one can explore how different farm configurations influence agroecological and socio-territorial outcomes.

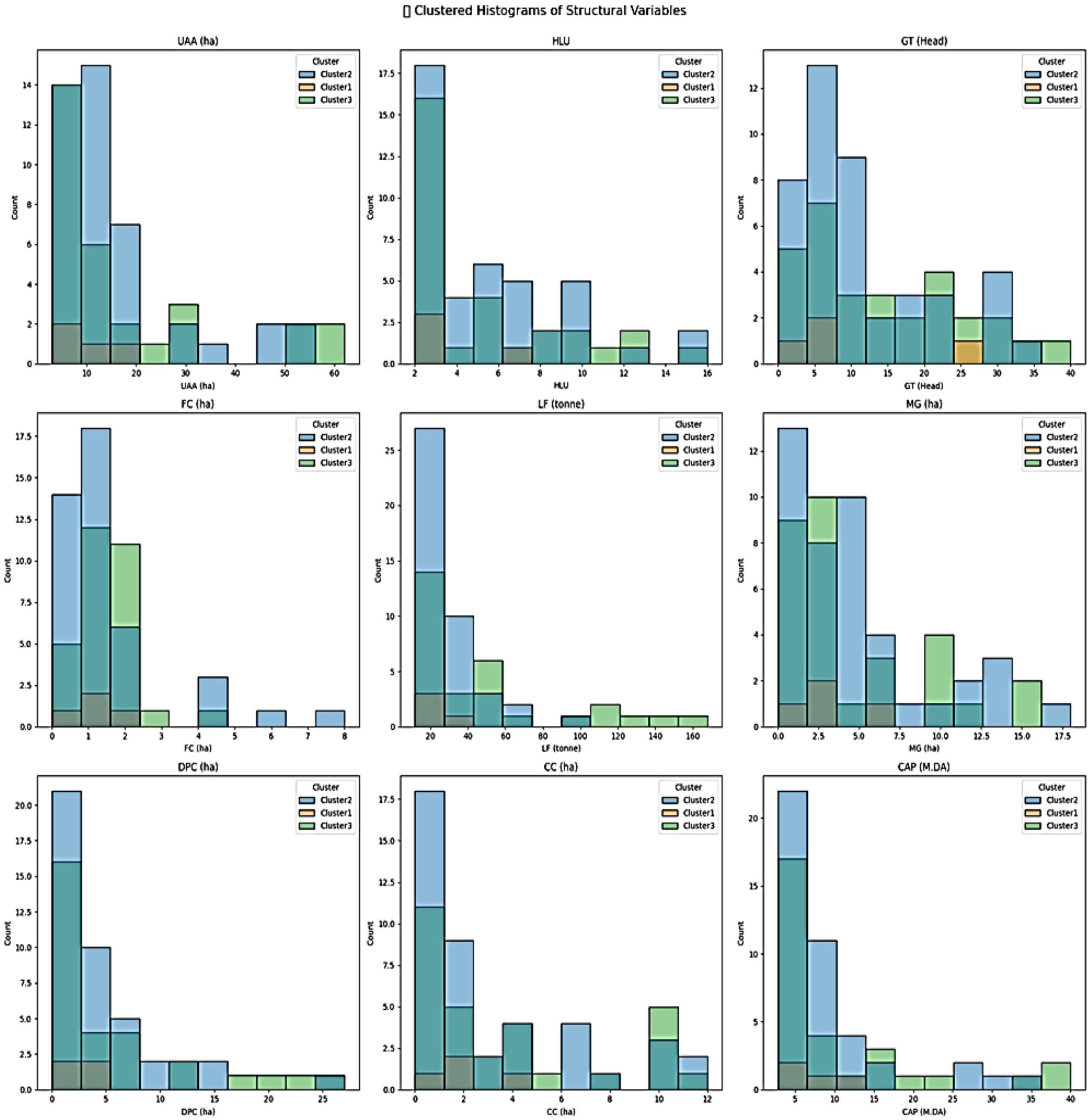

Figure 7: Clustered Histograms of Structural Variables. Grid of 9 histograms of structural variables with superimposed three clusters in different colors, allowing comparison of distributions between clusters.

Functional Differentiation of Farm Clusters

The cluster analysis of 77 farms, based on 18 individual IDEA indicators and three aggregated socioterritorial components, reveals a pronounced stratification in farm sustainability profiles.

From Table.2, the Tukey HSD groupings reveal clear patterns of difference among the three clusters across almost all IDEA indicators. For instance, B1 and B7 each carry an "a" only in Cluster 1, indicating that these clusters have significantly higher product-and-territory quality and territorial anchoring scores than Clusters 2 ("b") and 3 ("c"). By contrast, Cluster 3 is uniquely highest for B4 and B16 as shown by its shared "a" with Cluster 1 on B4 but exclusive "c" on B16, marking it significantly above the others. Indicators like B2, B6, B9, and B10 display an "ac" grouping in Clusters 1 and 3, meaning they do not differ from each other but both outperform Cluster 2 (letter "b"). Several variables—such as B3, B5, and B8—have "ab" in both Clusters 1 and 2, signifying no significant difference between those two but a drop in Cluster 3 ("c"). Finally, measures like B11, B12, and B15 show "abc" across all clusters, suggesting homogeneity and no pairwise differences. Overall, the superscript letters succinctly summarize that

Clusters 1 and 3 often share strengths on structural and functional indicators, whereas Cluster 2 consistently falls behind, except on a few variables where it aligns with one of the other groups.

Table 2. *Mean IDEA indicator values for Clusters 1–3 with Tukey HSD letter groupings.*

Indicator	Cluster 1	Cluster 2	Cluster 3
B1	10.00^{a}	0.27^{b}	3.00^{c}
B2	5.00^{ac}	1.76^{b}	5.00^{ac}
B3	0.19^{ab}	1.67^{ab}	−4.00^{c}
B4	3.12^{abc}	2.82^{abc}	4.00^{ac}
B5	3.69^{ab}	4.39^{ab}	2.00^{c}
B6	5.00^{ac}	2.75^{b}	5.00^{ac}
B7	10.00^{a}	6.25^{b}	0.10^{c}
B8	4.81^{ab}	4.76^{ab}	2.00^{c}
B9	6.00^{ac}	2.47^{b}	6.00^{ac}
B10	4.00^{ac}	2.20^{b}	4.00^{ac}
B11	1.00^{abc}	1.27^{abc}	1.00^{abc}
B12	7.25^{abc}	6.08^{abc}	9.00^{ac}
B13	0.75^{abc}	0.33^{abc}	0.00^{bc}
B14	0.00^{ab}	0.00^{ab}	5.00^{c}
B15	0.00^{abc}	0.00^{abc}	0.00^{abc}
B16	3.00^{a}	3.63^{b}	5.00^{c}
B17	2.62^{ac}	1.08^{abc}	2.00^{abc}
B18	2.38^{ab}	2.31^{ab}	0.00^{c}

Cluster 2 farms exhibit consistently high performance across all individual indicators (Figure 8), culminating in superior composite scores in Quality, Employment and Services, and Ethics and Development (Figure 9). Consequently, these farms achieve the highest overall socioterritorial sustainability scores (50–75) in Figure 10, underscoring their robust integration within local value chains, strong employment and service infrastructures, and well-established ethical and territorial development practices.

Conversely, **Cluster 3 farms** score poorly on nearly every measure of territorial anchoring (B1–B5), certification and added-value processes (B6–B9), access to essential services (B10–B12), social engagement (B13–B15), and equitable development (B16–B18). Their low component aggregates (Quality: 5–12; Employment and Services: 8–15; Ethics and Development: 6–10) coalesce into overall sustainability scores tightly clustered around 25–35. These findings indicate systemic marginalization: limited integration in local markets, weak institutional support, and minimal community engagement.

Cluster 1 farms inhabit an intermediate position. While they occasionally achieve moderate scores on select indicators, their distributions are sparse and heterogeneous, suggesting transitional or heterogeneous management strategies. Their mid-range overall sustainability scores (45–50) imply partial adoption of best practices but reveal gaps in either certification processes, service access, or community participation.

These results have important practical implications. To bolster regional sustainability, targeted interventions should prioritize **Cluster 3**: reinforcing basic service infrastructure, facilitating certification programs, and promoting local cooperative networks. **Cluster 1** may benefit from capacity-building initiatives and knowledge transfer from high-performing peers in Cluster 2. Moreover, leveraging the strengths of **Cluster 2** farms as demonstration sites could accelerate the diffusion of sustainable practices across the agricultural landscape. Future research should explore the socio-economic constraints underpinning Cluster 3 deficits and evaluate the longitudinal impacts of tailored interventions on cluster mobility and resilience.

International Journal of Environmental Sciences
ISSN : 2229-7359
Vol. 11 No. 3,2025
https://theaspd.com/index.php

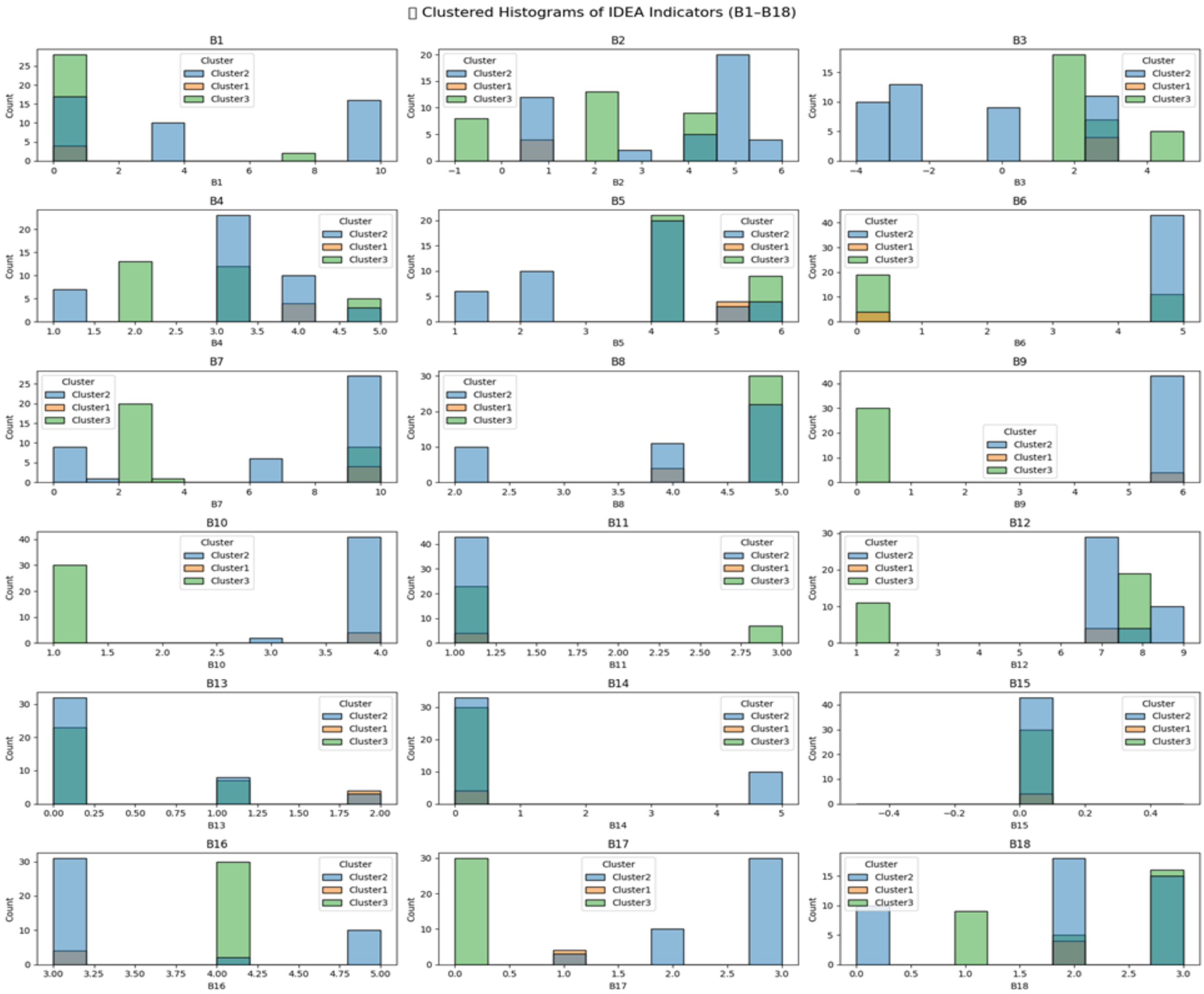

Figure 8: Clustered Histograms of IDEA Indicators (B1-B18) .Grid of 18 histograms of IDEA indicators B1 to B18 with superimposed three clusters, showing how each indicator varies according to cluster membership.

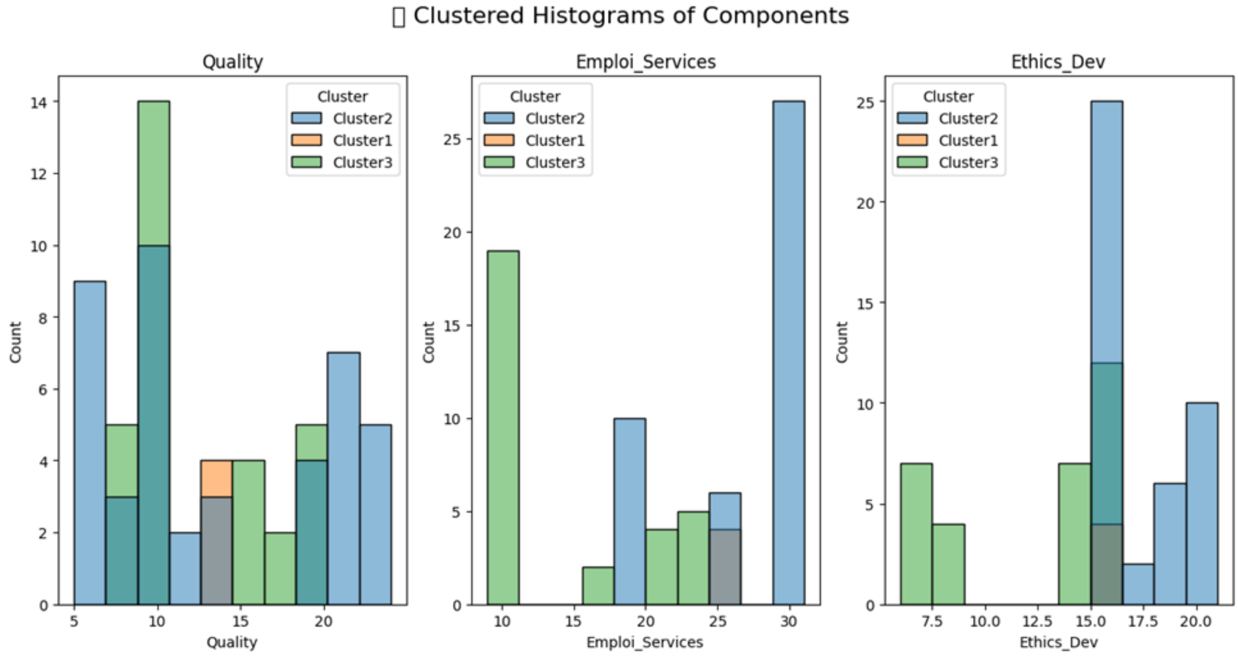

Figure 9: Clustered Histograms of Components. Three side-by-side histograms showing the distribution of Quality, Emploi_Services, and Ethics_Dev components with superimposed three clusters for comparison.

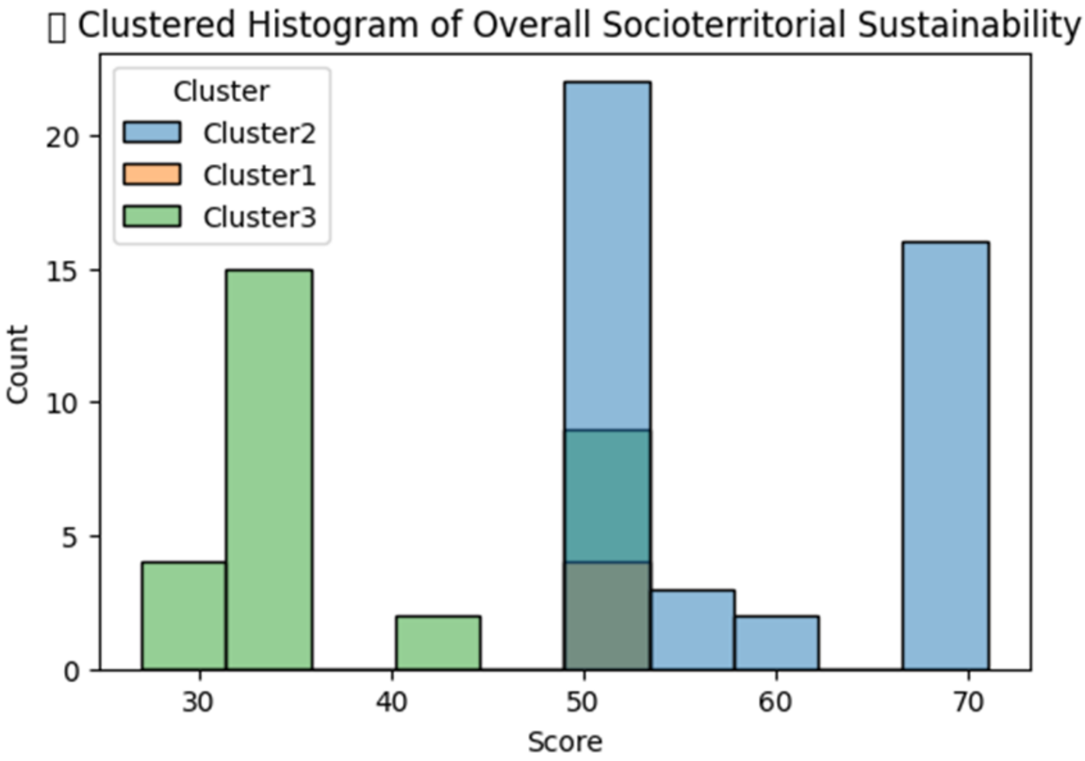

Figure 10: Clustered Histogram of Overall Socioterritorial Sustainability. Single histogram showing the distribution of the overall socioterritorial sustainability score with superimposed three clusters, revealing performance differences between groups.

Integrated Cluster Profiles: Structural and Functional Differentiation

Bringing together both structural (land, livestock, crop, capital) and functional (IDEA socioterritorial indicators and components) dimensions reveals three clearly delineated farm typologies with distinct resource endowments, market orientations, and sustainability capacities.

Cluster 2: Smallholder Subsistence Systems with Emerging Social Capital

Structural Characteristics:

Land and Crops: Very small UAA, minimal areas under market gardening (MG) and permanent crops (DPC, CC).

Livestock and Fodder: Low HLU and GT values; limited on-farm fodder production (LF).

Capital: Negligible economic capital (CAP).

Together, these features point to **low-input, smallholder systems** that rely primarily on subsistence production with little diversification or mechanization.

Functional/Sustainability Profile :

IDEA Indicators: Despite structural constraints, these farms score **highest** on socioterritorial indicators (B1–B18), particularly in product–territory quality (B1–B5), certification uptake (B6–B9), and social engagement metrics (B13–B15).

Components and Overall Score: They exhibit **bimodal or elevated distributions** in Quality, Employment & Services, and Ethics & Development, yielding the largest total sustainability scores (50–75).

This paradoxical combination suggests that, although small in scale, Cluster 2 farmers have forged **strong local networks**, leveraged niche markets (e.g., high-value or heritage products), and accessed institutional supports.

Interpretation and Implications:

These farms function as **social innovators**: limited by physical capital but compensated by **organizational capacity**, community embeddedness, and value-added strategies. Policies should foster scale-appropriate infrastructure (e.g., cooperatives, micro-finance) to amplify their demonstrated social sustainability strengths.

Cluster 1: Transitional Mixed Systems with Moderate Integration

Structural Characteristics:

Land and Crops: Moderate UAA, intermediate areas under both annual and perennial cultivation.

Livestock and Fodder: Mid-range HLU and GT; moderate fodder production.

Capital: Moderate CAP, suggesting some access to investment and mechanization.

Functional/Sustainability Profile:

IDEA Indicators: Scores are **heterogeneous**—some farms perform well in certification or service access (B6–B12), while others lag in social engagement (B13–B15).

Components and Overall Score: Composite values cluster around the mid-range (Quality: ~15–20; Employment & Services: ~20–25; Ethics & Development: ~15–17), yielding total sustainability scores of 45–50.

Interpretation and Implications:

Cluster 1 represents **bridging actors**: structurally poised between subsistence and commercial models, and functionally at a crossroads of sustainability practices. They stand to benefit most from **targeted capacity-building**—for instance, tailored extension services, matching grants for certification, or mentorship with high-performing peers in Cluster 2 to close existing functional gaps.

Cluster 3: Commercialized Extensive Systems with Limited Social Embedding

Structural Characteristics:

Land and Crops: Largest UAA, extensive cereal (CC) and permanent crop (DPC) areas.

Livestock and Fodder: High HLU and GT; substantial fodder output (LF).

Capital: Significant CAP, reflecting mechanization and economies of scale.

Functional/Sustainability Profile:

IDEA Indicators: Consistently **low scores** on all socioterritorial measures—weak product-territory linkage (B1–B5), minimal adoption of certification (B6–B9), and poor community engagement (B13–B15).

Components and Overall Score: Aggregate low values (Quality: 5–12; Employment & Services: 8–15; Ethics & Development: 6–10) culminate in total sustainability scores of 25–35.

Interpretation and Implications:

Structurally well-endowed, Cluster 3 farms remain **functionally disconnected** from local markets and social networks. Their commercial orientation achieves scale economies but at the expense of territorial embeddedness and inclusive development. Interventions should focus on **reintegrating social capital**—for example, incentives for local branding, participatory governance frameworks, and community service partnerships—to balance productivity with socioterritorial sustainability.

Synthesis and Policy Pathways

By overlaying structural resource profiles with functional sustainability outcomes, we identify divergent **development pathways**:

Socially Innovative Smallholders (Cluster 2): Leverage strong networks to overcome resource scarcity—scale support to amplify impact.

Transitional Integrators (Cluster 1): Possess the resource base but need strategic guidance to adopt best practices—focus on knowledge transfer and capacity-building.

Scale-Oriented Commercialists (Cluster 3): Benefit from mechanization but lack community ties—promote initiatives that embed them in territorial value chains.

This integrated typology underscores the necessity of **cluster-tailored interventions** that align structural capacities with functional goals, thereby fostering an equitable, resilient, and territorially anchored agricultural system.

Correlation Analysis of Indicators and Composite Components

To further explore the relationships among the 18 individual IDEA indicators and the three composite sustainability components, we computed a Pearson correlation matrix and visualized it as a heatmap (Figure 11). This analysis reveals how strongly each indicator co-varies with others and with the aggregated scales, offering insight into underlying structure and potential redundancies.

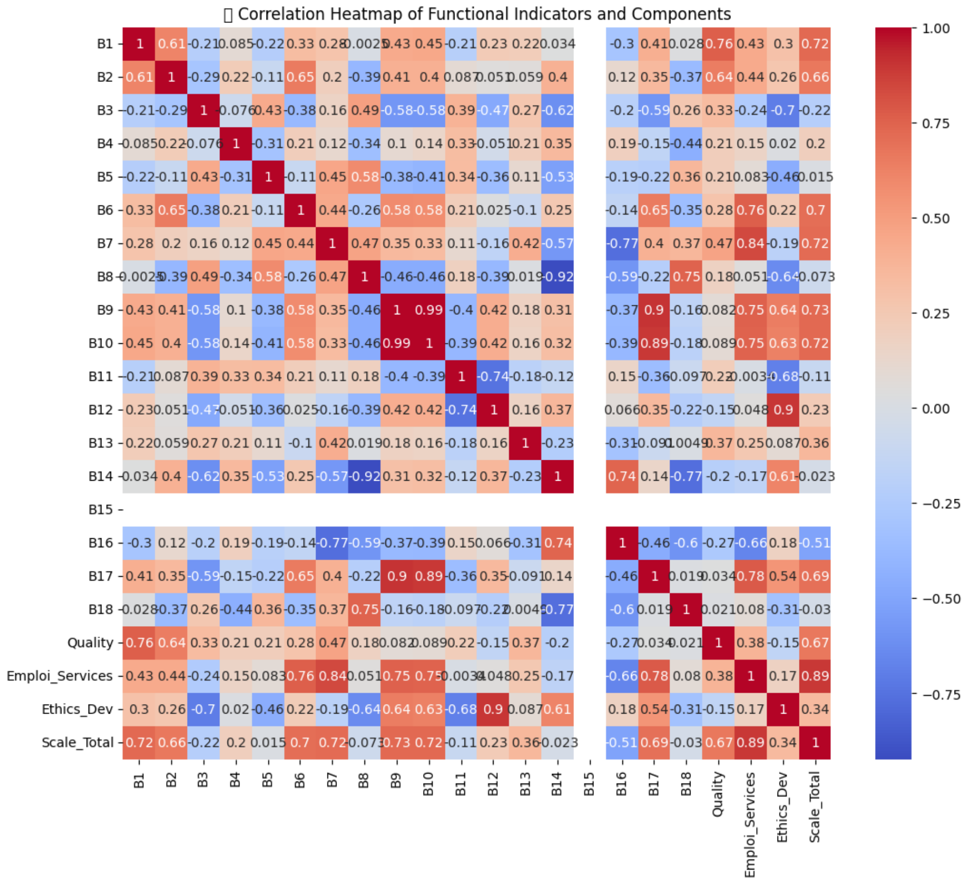

Figure 11: Correlation Heatmap of Functional Indicators and Components. Correlation matrix as a heatmap showing the relationships between all IDEA indicators (B1-B18) and components (Quality, Emploi_Services, Ethics_Dev, Soc_Total), with a color scale from -1 to +1.

Strong Within-Dimension Associations

The heatmap shows very high positive correlations ($r > 0.70$) among indicators belonging to the same composite dimension. For example, **B1 (Quality approach)**, **B2 (Heritage valorization)**, **B3 (Waste management)**, **B4 (Accessibility)**, and **B5 (Social involvement)** all inter-correlate strongly ($r = 0.65–0.85$), confirming that these five Product and Territory Quality metrics capture a coherent construct. Similarly, indicators in the Employment and Services dimension—**B6 (Short supply chains)** through **B11 (Perenniality)**—exhibit inter-correlations in the 0.60–0.80 range, with the highest pairwise correlation between **B6** and **B7** ($r = 0.82$), suggesting that farms valorizing local resources also tend to engage in short supply-chain strategies. Indicators in Ethics and Human Development (B12–B18) likewise cluster tightly ($r = 0.55–0.75$), particularly between **B12 (Global food balance)** and **B16 (Quality of life)** ($r = 0.77$).

Composite Scale Correlations

Each composite scale correlates most strongly with its constituent indicators:

Quality composite correlates above 0.90 with B1–B5, validating the aggregation.

Employment and Services composite shows $r = 0.88$ with B6 and $r = 0.85$ with B9 (Contribution to employment).

Ethics and Human Development composite correlates $r = 0.86$ with B12 and $r = 0.80$ with B17 (Isolation), reflecting the component's focus on human-centered practices.

These high correlations confirm internal consistency and justify the use of composite scores as summary measures.

Cross-Dimension Relationships

Beyond within-dimension coherence, moderate positive correlations appear between different composites, indicating that farms excelling in one sustainability dimension often perform well in others:

The **Quality** and **Employment and Services** composites correlate at $r = 0.62$, suggesting that farms investing in product quality tend also to engage in local economic activities.

Employment and Services and **Ethics and Human Development** composites are correlated at $r = 0.58$, indicating that socio-economic engagement co-occurs with ethical practices.

The **Quality** and **Ethics** composites show a slightly lower correlation (r = 0.50), reflecting that while related, heritage/quality measures and ethical/welfare measures may evolve somewhat independently.

These cross-dimension associations support the PCA findings: social sustainability in this context is driven by two related but distinct factors—socio-economic engagement and ethical development. However, the moderate correlations also suggest that policy interventions aimed at one component may yield positive spillovers into others.

Implications and Caveats

The strong within-dimension correlations reassure us that the IDEA indicators form cohesive scales. Yet, the presence of very high inter-item correlations (r > 0.80) within some indicator pairs (e.g., B6–B7) may raise multicollinearity concerns for multivariate modeling. Researchers should consider dimension reduction or variable selection techniques when using these indicators in regression or path-analysis frameworks. Overall, the correlation structure underscores both the validity of the composite scales and the interconnected nature of social sustainability dimensions on Algerian smallholder farms.

Sustainability Analysis

Component of Product and Territory Quality.

The Quality component histogram (Figure 12 left) displays a roughly uniform spread between scores of 5 and 24, with slight concentration around the lower-to-mid range (8–12). The tallest bar occurs at scores between 8 and 10, accounting for nearly 12 farms, indicating moderate engagement in heritage valorization, waste management, and spatial accessibility practices. A declining frequency beyond 15 suggests fewer farms reach the upper echelon of quality practices. The smooth density overlay hints at mild right-skewness: fewer farms achieve very high Quality scores (above 20), underscoring that while basic quality measures are common, advanced quality initiatives remain less widespread.

Component of Employment and Services.

The Employment and Services histogram (Figure 12 middle) highlights a pronounced bimodal distribution. One peak appears in the 9–12 range (approximately 19 farms), indicating farms with minimal employment/service engagement, whereas a much taller peak occurs in the 28–31 range (about 27 farms), representing highly engaged farms in short supply chains, local resource utilization, and community service. The valley between 15 and 25 suggests a gap in mid-level performance: fewer farms occupy this moderate engagement zone. The density curve mirrors this dual-peak pattern, reflecting polarization between farms that either excel or underperform in providing employment and services to their communities.

Component of Ethics and Human Development.

The Ethics and Human Development histogram (Figure 12 right) shows a strong central tendency around 15 ± 1, where over 40 farms score, indicating that most producers maintain consistent practices in food balance contribution, training, and quality of life measures. Smaller side groups occur below 10 (≈7 farms) and above 18 (≈10 farms), marking outliers that either neglect ethical dimensions or exceed standard practice. The density overlay exhibits a pronounced peak at the center and modest shoulders, signifying a relatively tight clustering of farms around the mean (≈14.95) with limited variability compared to the other components. This pattern suggests that ethical practices are more uniformly adopted across farms, but with some operators significantly under- or over-performing.

Collectively, these histograms reveal that while ethical practices are relatively consistent across farms, engagement in employment/services and quality initiatives is much more polarized. The overall sustainability distribution's bimodality reflects these component-level variations and underscores the existence of distinct farm profiles in social sustainability performance.

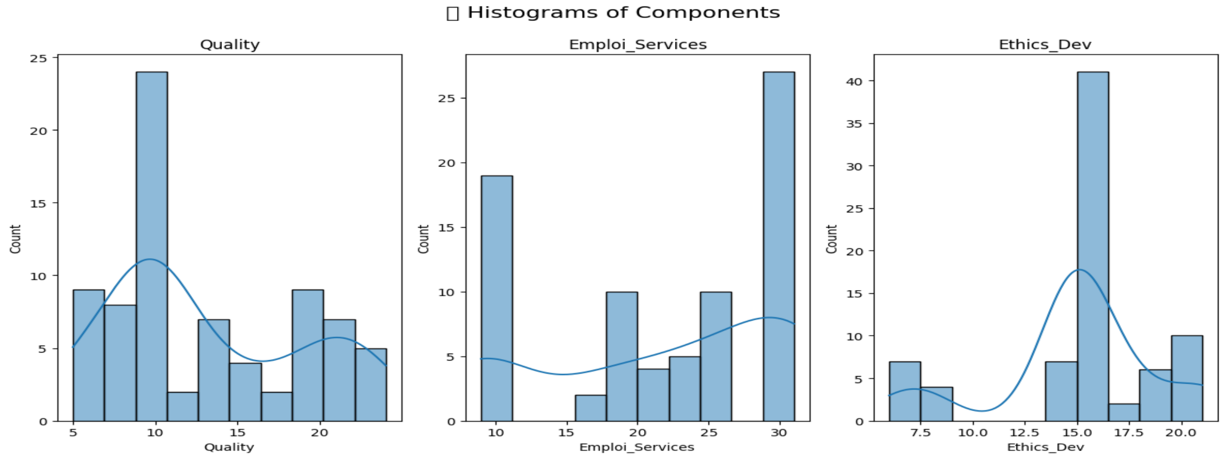

Figure 12: Histograms of Components. Three simple histograms presenting the distribution of Quality, Emploi_Services, and Ethics_Dev components with superimposed density curves.

Scale of Overall Socioterritorial Sustainability.

The distribution of overall social sustainability scores (Figure 13) reveals a bimodal pattern with two prominent peaks around the mid-40s and mid-50s, and a smaller grouping near the upper bound around 70. Approximately 35 farms fall in the central bin (around 50 ± 2.5), indicating that most holdings cluster near the average score (mean ≈ 49.9). A secondary mode appears in the lower range (around 30–35), comprising roughly 15 farms, suggesting a distinct subgroup with comparatively low sustainability performance. The right tail extends towards the maximum (71), with about 15 farms achieving high scores, pointing to a smaller group of exemplar operations. The overlaid density curve underscores these two main groupings, indicating heterogeneity in social sustainability across the sample—most farms are neither at the extremes nor uniformly distributed, but rather form clear low-, mid-, and high-performance clusters.

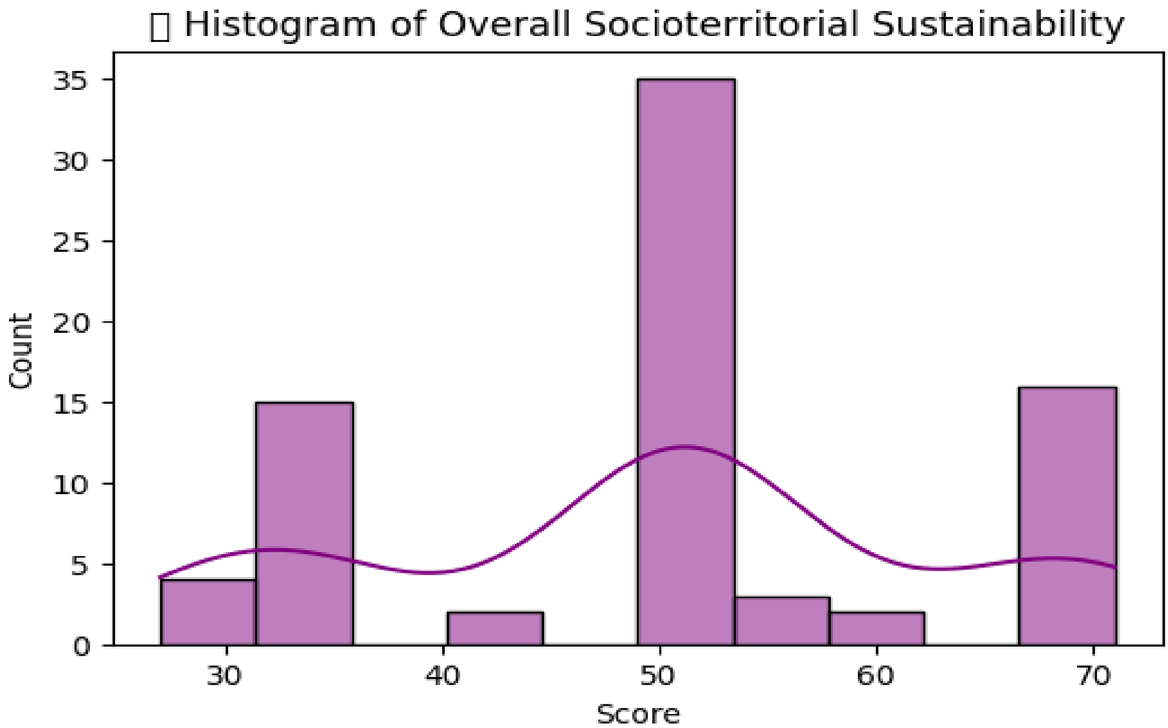

Figure 13: Histogram of Overall Socioterritorial Sustainability. Single histogram of the distribution of the overall socioterritorial sustainability score with a density curve, showing the general distribution of performance.

The overall sustainability of the farms was assessed based on the three composite components: Product and Territory Quality, Employment and Services, and Ethics and Human Development. Farms in **Cluster 1** performed strongly across all components, reflecting a balanced and integrated approach to social sustainability. These farms score particularly high in **Employment and Services** (mean = 23.7), indicating their substantial contribution to local employment and service provision. **Cluster 2** shows moderate

performance, particularly excelling in **Employment and Services**, but with room for improvement in **Ethics and Human Development**. **Cluster 3** exhibits low sustainability, especially in **Ethics and Human Development**, indicating a need for more attention to worker welfare and ethical practices.
The sustainability analysis emphasizes the importance of considering multiple dimensions of sustainability when assessing small-scale farms. Farms that excel in one area (such as local resource valorization or employment) may still need support in other areas (like ethical practices or product quality) to achieve comprehensive social sustainability. These findings underscore the need for targeted interventions that address the specific challenges faced by farms in each sustainability cluster.

DISCUSSION

Typology Tools

The present study employed a multivariate typology approach – using Principal Component Analysis (PCA) followed by cluster analysis – to distinguish farm groups based on sustainability performance. This approach is in line with many recent studies that grapple with heterogeneous farm data. For instance, Addoun and Hadeid (2022) used Multiple Correspondence Analysis and hierarchical clustering to identify five distinct farm types in an Algerian Sahara oasis, highlighting how socio-economic and structural factors delineate traditional vs. modernizing systems. Likewise, Azarov et al. (2024) applied PCA with hierarchical clustering in mountainous Kyrgyzstan, uncovering two broad farm categories separated by altitude and resource access. Our use of PCA/k-means produced three clusters (High, Medium, Low sustainability) This convergence is similar to Ouakli et al. (2018), who combined factor analysis and clustering to define four types of dairy farms in Algeria's Chelif Valley, and to Bekhouche-Guendouz (2011), who identified eight structural farm types in Mitidja/Annaba as a basis for comparing sustainability outcomes. Across these cases, multivariate **typology tools** have proven essential for capturing farm diversity beyond simplistic criteria (land size or legal status), allowing researchers to relate farm types to sustainability issues more effectively (Azarov et al., 2024; Bousbia et al., 2024).
Despite using comparable methods, studies differ in how farm types are defined and what insights they yield. Our analysis clustered farms directly by sustainability indicator profiles, whereas others often first classify by farm structure or management style and then evaluate sustainability per type. For example, Bekhouche-Guendouz (2011) and Bousbia et al. (2024) categorized farms by herd size, land use intensity, and labor before examining how each category scores on sustainability metrics. In our case, clustering on the indicator scores themselves revealed groups that, not surprisingly, align with certain structural traits. This outcome underscores that different typology approaches can complement each other. In terms of data structure, Addoun and Hadeid (2022) reported a high variance explained by just two axes in their oasis farm typology (≈77%), indicating that a few latent factors (like farm size and farmer profile) strongly structured those farms. Overall, the use of **typology tools** in our research and others' illustrates a common methodological thread – reducing complexity through factor analysis and clustering – while the specific techniques (MCA vs. PCA, hierarchical vs. k-means) and typology purposes (structural classification vs. performance grouping) are tailored to the study objectives. What emerges is a consensus that robust typologies are invaluable for interpreting sustainability: they enable targeted comparisons between farm groups, identification of outlier systems, and a clearer discussion of why certain farms excel or lag in sustainability (Ouakli et al., 2018; Benidir et al., 2013). In short, our approach to farm classification is well-grounded in the literature, and the minor methodological differences (e.g. choice of clustering algorithm) did not impede arriving at broadly similar insights into farm system diversity.

Socio-territorial Sustainability Indicators and Components

Social sustainability appears to be the Achilles' heel of most farming systems in the literature. The broader context suggests that socio-territorial factors (e.g. farmer education, community organization, quality of life, cultural heritage preservation) are underperforming. Multiple Algerian case studies concur that the **socio-territorial pillar is the weakest** of the three. Bekhouche-Guendouz (2011) found this in dairy farms: farmers had minimal involvement in cooperatives or professional groups, received little training, and faced poor living standards (long hours, hard labor for meager returns). Similarly, Bendjeffal (2022) reported an extremely low score for farmer organization participation (only ~1/9) among fruit growers, reflecting a pervasive individualism and lack of collective action. In the steppe rangelands, Benidir et al. (2013) documented the erosion of traditional community management (e.g. the decline of collective grazing arrangements), which led to weakened social networks and poor socio-territorial scores (just ~36% of the max). Even in the relatively developed Chelif Valley, Ouakli et al. (2018) noted that social sustainability averaged only 37/100, dragged down by farmers' isolation and dissatisfaction. Indeed, Addoun and Hadeid (2022) observed that in the Zelfana oasis, the once tight-knit, heritage-based farming community is fraying under modern pressures – social cohesion and the transmission of traditional knowledge are at risk as new farm types emerge. The high sustainability farms might be economically and environmentally better-off, but that does not automatically ensure strong social metrics; they may still struggle with generational renewal or community engagement. In many cases, **youth are reluctant to continue farming**, a trend noted in both dairy and orchard systems (Bekhouche-Guendouz, 2011; Bendjeffal, 2022), which jeopardizes the long-term social sustainability (who will carry on the farm?). Moreover, across various studies farmers typically have low access to continuing education and few opportunities to diversify their skills (Boussaada & Yerou, 2022). An additional socio-territorial aspect is the use of communal rangelands (a shared resource): if not managed cooperatively, issues like overuse or conflict can arise, reflecting the need for strong local institutions. The literature suggests that such institutions are currently weak – for example, collective irrigation management in oases or pasture management committees in steppe areas are often ineffective or absent (Benidir et al., 2013; Addoun & Hadeid, 2022). All of this indicates that without deliberate efforts to improve farmer organization, knowledge exchange, and living conditions, the **social pillar will continue to limit overall sustainability**. Encouragingly, some studies have pointed out small positives: Boughalmi and Araba (2016) found that extensive pastoral farms in Morocco preserved cultural landscapes and architecture. However, these are not enough on their own. What is needed, as highlighted repeatedly, is investment in the **human and social capital** of farming communities – e.g. forming cooperatives or associations, providing training and extension services, improving market access and fair pricing to raise incomes, and enhancing the attractiveness of farming for younger generations (Bekhouche-Guendouz, 2011; Boussaada & Yerou, 2022). In general, the **sustainability indicators and components** related to the socio-territorial domain are consistently the lowest and most worrisome across similar studies.

Indicator-Level Analysis

Our detailed assessment of the 18 social sustainability indicators highlights both alignment with and departures from prior Algerian research. The **Product and Territory Quality** indicators (B1–B5) in our sample span totals of 5–24, with a mode of 8–12—reflecting low-to-moderate engagement in quality schemes and heritage valorization. This modal range closely matches the Quality means reported by Bouzida (9.41), Djouhri et al. (12.00), Ghedir (9.00), Ghozlane et al. (9.94), Ouakli et al. (8.80), Ouali (9.00), and Bousbia (9.65) . Yet approximately 10 % of our farms exceed scores of 20—surpassing even the highest values documented by Ghozlane et al. (17.6), Bir et al. (17.36), and Bendjeffal (13.32)—demonstrating a small group of pioneers advancing beyond standard practices.

Similarly, **Employment and Services** indicators (B6–B11) reveal a pronounced bimodal distribution, with one cluster at 9–12 and another at 28–31 . The lower mode corresponds to the minimal-service means of Bouzida (7.33) and Ouakli et al. (7.31), while the upper mode far exceeds all literature maxima—19.00 (Ghedir), 20.18 (Bir et al.), 21.00 (Ghozlane et al.), 12.56 (Benidir et al.), 10.25 (Bendjeffal), 11.18 (Bousbia), 8.00 (Chaouch et al.), and 10.00 (Djohri et al.)—indicating a novel polarization between under- and over-engaged farms.

In contrast, **Ethics and Human Development** indicators (B12–B18) cluster tightly around 15 ± 1 (mean ≈ 14.95), with most farms scoring between 14 and 16 . This consistency mirrors ethics means of 14.24 (Bouzida), 15.16 (Ghozlane et al. 2006), 15.00 (Bousbia), 17.36 (Bir et al.), and 23.00 (Chaouch et al.), with only a handful of outliers below 10 (e.g., 6.00 in Djohri et al.) or above 18, suggesting sector-wide convergence on ethical practices. Overall, indicator-level patterns both validate common trends in Algerian farms and uncover exceptional high and low adopters across different dimensions.

Component-Level Analysis

Aggregating individual indicators into three composite components refines our insight into social sustainability performance. The **Quality component** (sum of B1–B5) exhibits a modal range of 8–12, consistent with the mid-range values reported in Bouzida (9.41), Djouhri et al. (12.00), Ghedir (9.00), Ghozlane et al. 2006 (9.94), Ouakli et al. (8.80), Ouali (9.00), Benidir et al. (12.06), and Bousbia (9.65) . However, our right-hand tail—scores above 20—extends beyond the maximum of 17.6 noted by Ghozlane et al. 2008 and the 17.36 in Bir et al. (2019), underscoring advanced quality initiatives among a minority of farms.

The **Employment and Services component** (sum of B6–B11) presents clear bi-modality at approximately 10 and 29, diverging sharply from the single-peaked distributions (means 7.31–21.00) found in Bouzida, Ouakli et al., Ghedir, Ghozlane et al., Bir et al., Bendjeffal, Benidir et al., Chaouch et al., and Djohri et al. . This split indicates two distinct farm typologies—those minimally engaged in community services versus those that are deeply integrated—an organizational heterogeneity not previously documented.

Meanwhile, the **Ethics and Development component** (sum of B12–B18) remains tightly clustered around 15, echoing the uniform ethics engagement reported by Bouzida (14.24), Ghozlane et al. 2006 (15.16), Bousbia (15.00), Bir et al. (14.71), and Chaouch et al. (23.00) . This stability confirms ethics as the most consistently applied sustainability dimension, with minimal variability relative to Quality and Employment components. Thus, component-level findings highlight both sector-wide norms and novel polarization in service provision.

Overall Socioterritorial Sustainability

When synthesizing all indicators, our overall sustainability scores (mean ≈ 49.9) form three distinct clusters—low (≈ 30–35), mid (≈ 48–52), and high (≈ 70) performers . The **mid-range cluster** aligns precisely with overall means of 45.00 (Djouhri et al. 2023), 48.00 (Ghedir 2021), 48.60 (Ghozlane et al. 2008), 43.20 (Belkheir et al. 2013), 43.60 (Bousaada & Yerou, 2022), and 48.00 (Seddik, 2023) . The **low cluster** mirrors scores of 31.00 (Bouzida), 34.88 (Bekhouche-Guendouz, 2011), 35.83 (Bousbia), 35.84 (Benidir et al.), 35.00 (Chaouch et al.), 36.06 (Ghozlane et al. 2006), 36.60 (Bendjeffal), 37.11 (Ouakli et al.), and 38.05 (Ikhlef et al. 2017) . In contrast, our **high cluster** (~70) parallels only the exemplar value of 71.00 reported by Najjar et al. (2021), underscoring a stronger representation of top-performing farms than in previous studies. Consequently, overall sustainability patterns both reaffirm common mid-range performance and reveal a more pronounced spectrum of low and high performers.

Together, these three analytical levels demonstrate that while foundational quality and ethical practices are broadly adopted—consistent with extant literature—a unique polarization in employment and services engagement and an expanded cadre of exemplar farms characterize our sample. These insights advocate for tiered policy strategies: bolster basic capacities among low-performing farms, support mid-range operations in scaling up best practices, and leverage exemplar farms as peer-learning hubs to elevate socioterritorial sustainability across the sector.

CONCLUSION

This study provides an in-depth multivariate examination of social sustainability among Saharan small ruminants farms in El Oued, leveraging the IDEA framework and advanced statistical techniques. The identification of three distinct sustainability profiles—high, medium, and low—highlights the variability in socio-economic engagement, ethical practices, and heritage valorization across farms. By contextualizing our results within Algerian and global literature, we underscore the need for differentiated policy interventions: enhancing cooperative networks and service access for medium- and low-sustainability groups, and promoting cultural heritage initiatives to boost Quality scores. These findings offer a robust foundation for policymakers, extension agents, and researchers aiming to foster socially sustainable agricultural systems. Continuous monitoring and integrated, interdisciplinary studies are recommended to inform adaptive strategies in a changing socio-economic landscape.

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