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Differentiation of Nephelium lappaceum producers in Honduras: perspectives for the inclusive rural bioeconomy

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Abstract

Background: This study analyzes the structural heterogeneity of Nephelium lappaceum (rambutan) producers in Atlántida, Honduras, establishing distinct typologies to evaluate their capacity to participate in the value chain and the emerging Inclusive Rural Bioeconomy.

Methodology: Multivariate statistical techniques were applied to primary data from 314 randomly sampled producers. Principal Component Analysis (PCA) reduced dimensionality, K-means clustering defined producer typologies, and Kruskal–Wallis tests validated socioeconomic and organizational differences across clusters.

Results: The analysis identified three distinct typologies, explaining 65.0% of the total variance and confirming marked agrarian dualism: Cluster 1 (91% of producers) represents small-scale, subsistence-oriented, low-capital farms; Cluster 2 (7%) comprises intermediate, innovative producers with higher organizational capital; and Cluster 3 (2%) consists of large-scale entrepreneurs with high capital concentration and direct market access (67% accessing financing). Structural inequality severely limits Cluster 1 from investing in value addition or capturing bioeconomic potential.

Originality: The scientific novelty lies in providing an empirically validated classification of high-value non-traditional crop producers in Central America. It directly links structural dualism to a differentiated policy framework for an Inclusive Rural Bioeconomy, leveraging underutilized bioactive compounds in rambutan byproducts (peel and seed).

Practical implications: Differentiated agricultural policies are required to mitigate inequality. Cluster 1 needs interventions focused on social capital and low-cost extension services, whereas Cluster 2 requires support for certification and collective valorization platforms to anchor added value to the territory.

JEL-Classification: Q12, Q18, O13

1. Introduction

Rural territories in Central America are shaped by deep structural inequalities that manifest in unequal access to land, technology, markets, and organizational capacities. In Honduras, these disparities are particularly visible in the department of Atlántida, a region characterized by high agroecological potential but also by persistent rural poverty, limited economic diversification, and increasing demographic pressures. Studies on territorial development in Latin America (Schejtman & Berdegué, 2004; Berdegué, Escobal & Bebbington, 2014) have consistently shown that these inequalities hinder productive inclusion and generate cycles of territorial stagnation.

In recent years, rural depopulation has emerged as an additional challenge in Atlántida. Similar to processes observed in Mediterranean Europe (Stockdale, 2016; Collantes & Pinilla, 2011), smallholder farmers—especially younger generations—face economic uncertainty, limited access to productive assets, and insufficient opportunities for value-added activities. These territorial constraints intensify outmigration

to urban centers or abroad, accelerating demographic imbalances that threaten the long-term resilience of rural economies (Bartkowski et al., 2022).

Against this background, the expansion of rambutan (Nephelium lappaceum) cultivation has gained importance as a non-traditional, high-value crop with growing domestic and regional demand. Rambutan production offers small and medium farmers an alternative pathway for income diversification, improved cash flow, and reduced vulnerability to market shocks affecting traditional crops such as coffee or citrus (De La Rosa-Esteban et al., 2023). The crop has also shown potential for vertical integration and value addition, particularly by by-products—peels and seeds—for nutraceutical and cosmetic applications (Arias-Cruz et al., 2016; Bhattacharjee et al., 2022).

Despite its potential, the capacity of rambutan to contribute to territorial development is not uniform. Preliminary evidence suggests significant heterogeneity among producers in terms of land size, technological adoption, market access, and organizational participation. These differences shape not only productivity and income but also the ability of producers to remain in rural areas, adopt innovations, and benefit from emerging bioeconomic opportunities (Lazaro Soto et al., 2024; Maldonado-Méndez et al., 2024).

However, the lack of a systematic characterization of these producers represents a critical gap in current territorial planning. Without understanding the specific structural constraints of each producer typology, public interventions risk being ineffective or, worse, exacerbating existing inequalities by favoring only those with better initial assets. In the current reality of Central America, where climate change and market volatility demand rapid adaptation, identifying these typologies is not merely an academic exercise; it is a fundamental requirement for designing inclusive bioeconomic strategies that can effectively mitigate rural depopulation and foster territorial resilience.

This study seeks to determine the structural heterogeneity of rambutan producers in Atlántida to evaluate their capacity for participation in an inclusive rural bioeconomy. Consequently, the primary purpose of this research is to establish a robust producer typology that serves as a diagnostic tool and strategic framework for targeted territorial development policies aimed at reducing rural depopulation. To achieve this goal, the following specific tasks are proposed: (1) to characterize producers based on productive and socioeconomic variables; (2) to identify clusters using multivariate statistical approaches; and (3) to discuss the implications for rural cohesion and bioeconomic integration.

2. Literature Review

2.1 Rural Depopulation and Territorial Disparities

Rural depopulation has become a defining feature of territorial transformations in many regions of the world. In Europe, extensive research shows how demographic decline is associated with structural weaknesses, weak market integration, and persistent inequalities in rural areas (Stockdale, 2016; Collantes & Pinilla, 2011). These studies highlight that depopulation is not merely a demographic process, but a

symptom of deeper territorial imbalances related to limited opportunities, scarce public services, and insufficient productive diversification.

In Latin America, although depopulation follows different historical trajectories, patterns of youth emigration, declining rural labor availability, and aging farmer populations have been widely documented (CEPAL, 2021; Carlson, 2019). These trends are closely linked to territorial disparities, where rural economies remain marginalized from national development processes (Bernard et al., 2023; Berdegué, Escobal & Bebbington, 2014). In Honduras, the department of Atlántida reflects these tendencies: despite its agroecological potential, many communities face limited access to markets, low levels of productive infrastructure, and a lack of stable income opportunities, encouraging young people to migrate.

Under this lens, territorial cohesion—defined as the reduction of spatial inequalities and the strengthening of local capacities—becomes essential for enabling balanced development (Sánchez-Zamora & Gallardo-Cobos, 2020). Understanding producer heterogeneity is therefore crucial because differentiated groups possess distinct capacities to remain, invest, and contribute to territorial vitality.

2.2 Structural Heterogeneity and Agrarian Dualism in Latin America

The concept of structural heterogeneity, introduced by Barbier & Bugas (2014), describes how economic systems in Latin America coexist with highly unequal levels of productivity, technology, and access to resources. This heterogeneity generates barriers to inclusion and traps small producers in low-productivity activities while enabling larger producers to integrate into dynamic markets (Estrada-Gil et al., 2022).

In the agrarian sector, this idea connects with the long-standing notion of agrarian dualism (Kay & Vergara-Camus, 2017; de Janvry & Sadoulet, 2000), which emphasizes the coexistence of modernized, capital-intensive agricultural units and smallholder farms with restricted access to land, credit, and innovation. These structural differences directly affect income generation, competitiveness, and long-term sustainability.

In the context of rambutan production in Atlántida, structural heterogeneity manifests in the variability of cultivated area, technological levels, market participation, and available labor. Identifying producer typologies becomes a methodological bridge to understanding how these inequalities are expressed and how they shape opportunities for rural development.

2.3 Agricultural Producer Typologies: Approaches and Relevance

Typology studies are essential for designing differentiated interventions in agricultural systems (Cuevas-Reyes et al., 2024; Cáceres et al., 2023). They allow researchers and policymakers to identify groups of producers with similar characteristics in terms of scale, technology, labor, income structure, and market orientation. These analyses have been widely applied to coffee systems in Central America, cacao in the Caribbean, and various fruit systems (Chollakup et al., 2020; Gliessman, Rosset & Patel, 2019; Altieri & Nicholls, 2017).

Typologies provide insights into how producers navigate complex environments shaped by climate change, price volatility, technological gaps, and limited organizational integration. For emerging crops such as rambutan, which combine traditional production practices with new market opportunities, typologies help identify strategic groups capable of driving territorial transformation (Cresto Aleina et al.. 2024; Borja Bravo et al., 2018; Campos Saldaña et al., 2022).

2.4 Inclusive Rural Bioeconomy: Inclusive, Circular, and Territorial Perspectives

The expansion of Inclusive Rural Bioeconomy has opened new possibilities for rural development by promoting value chains based on renewable biological resources. However, the concept is diverse and often contested. Bugge, Hansen & Klitkou (2016) identify three main visions of Inclusive Rural Bioeconomy: biotechnology-driven, bioresource-based, and socio-ecological. For rural contexts, the socio-ecological perspective is the most relevant because it emphasizes inclusion, territorial integration, and sustainable use of biodiversity (Corral et al., 2022; Kato et al., 2022).

Birner (2018) and Ramcilovic-Suominen & Pülzl (2018) argue that Inclusive Rural Bioeconomy strategies that fail to incorporate small-scale producers risk reinforcing existing inequalities. In contrast, an inclusive rural Inclusive Rural Bioeconomy seeks to enhance value-added opportunities, circular practices, and multi-product use—elements that are highly relevant for crops like rambutan, where by-products have growing commercial potential (Mier-Tous et al., 2023; Mihai, 2023).

2.5 Organizational Capital and Collective Action in Rural Development

Organizational capital—understood as the capacity of producers to coordinate, cooperate, and participate in collective institutions—is a critical determinant of rural development (Pretty, 2003; Ostrom, 1990). Strong organizations can improve market access, reduce transaction costs, facilitate technological adoption, and strengthen bargaining power.

In many Central American territories, weak organizational structures have limited the ability of small producers to integrate into dynamic value chains (Lombardo, 2025; Borja Bravo et al., 2018). For rambutan producers in Atlántida, organizational capital becomes especially important due to dependence on intermediaries, the need for coordinated marketing strategies, and the potential for collective processing or packaging initiatives.

Understanding the organizational capacities of each typology is therefore essential for identifying realistic pathways toward territorial cohesion and an Inclusive Rural.

3. Methodology

Study Area and Justification

3.1 Geographic and Socioeconomic Context of Atlántida

The department of Atlántida is located along the northern Caribbean coast of Honduras and is characterized by a diverse mosaic of agroecological zones. Its humid tropical climate, fertile soils, and abundant water resources make it a highly suitable region for perennial and semi-perennial fruit production. Atlántida includes both coastal and mountainous territories, with small rural communities embedded within landscapes marked by biodiversity and rich ecological potential.

Despite these natural advantages, the department faces several socioeconomic challenges that are common to rural areas in Central America. Poverty levels remain above national averages, infrastructure is unevenly distributed, and access to markets is often limited by transportation constraints. The rural population is increasingly affected by migration to urban

The selection of Atlántida and rambutan as the focus of this study is crucial due to the marked contrast this production model presents compared to the dominant agrarian schemes in other Honduran regions. While the Pacific Coast and the South of the country are characterized by the predominance of sugarcane monoculture or extensive cattle ranching, models that generate high dependence on external markets, intensive use of agrochemicals, and limited cash flow for smallholders (CEPAL, 2021), Atlántida is positioned as a zone of agroecological diversification.

In contrast to the extreme vulnerability to climate change and price volatility that affects coffee-producing regions in the Western Zone, rambutan offers a perennial and high-value non-traditional alternative. Studying its dynamics here allows us to evaluate whether a crop with bioeconomic and niche potential can be an effective strategy to mitigate inequality and rural depopulation, providing stable incomes and value-added opportunities that traditional commodity systems fail to generate. This comparative analysis establishes the strategic relevance of the research.

Source: Own elaboration

3.2. Sampling Design and Study Population

The target population consisted of 1,696 rambutan producers registered in the census of the Productive Agroforestry Systems Project (SAP), implemented by Rainforest Alliance in 2024. Of these, 642 had complete records 4, and a simple random sample of 314 producers was selected, with a 95% confidence level and a sampling error of ± % 5 (Table 1).

Table 1
Number of randomly selected producers

Municipality	No. of Producers selected	Proportion
Arizona	24	0.08
La Ceiba	6	0.02
El Porvenir	9	0.03
Esparta	47	0.15
Jutiapa	2	0.01
La Masica	72	0.22
San Francisco	54	0.17
Tela	100	0.32
Total	314	1.00
Source: Authors' own elaboration		

The 314 producers constituted the final valid sample used for the multivariate analysis. Prior to executing the analysis, the dataset underwent a meticulous data cleaning process to ensure the consistency and quality of all key variables, addressing potential missing values or outliers without reducing the representative sample size. This approach ensured that the statistical analysis (PCA and clustering) was conducted on the full representative sample selected for the study.

As presented in Table 2, the descriptive statistics confirm a marked structural heterogeneity within the rambutan producer population (n = 314). Variables related to scale and economics, such as Number of Rambutan Trees (SD 980) and Income from Harvest (SD 150,000 Lempiras [6,036.97 $ US]), exhibit extremely high dispersion relative to their means, and show a significant positive Skewness (e.g., 5.38 for the number of trees). This strong asymmetry indicates an unequal concentration of resources among a few large producers (outliers) and validates the subsequent use of non-parametric tests and Principal Component Analysis for dimensionality reduction, given the lack of normality in the data distribution.

Table 2
Descriptive Statistics of Key Variables in the Sample (N = 314)

Variable	Type	Mean	Standard Deviation (SD)	Minimum	Maximum	Skewness Coefficient
Scale and Economic Variables						
Total Farm Area (ha)	Continuous	6.09	**7.95**	**1.4**	**73.5**	**3.5**
Number of Rambutan Trees	Continuous	466	**980**	**20**	**5,000**	**5.38**
Income from Harvest (The exchange rate is 24.8469 Lempiras per US Dollar.)	Continuous	3,895.73	**6,036.97**	**0**	**450,000**	**4.5**
Forest Area (ha)	Continuous	1.83	**3.50**	**0.0**	**35.0**	**5.0**
Social/Management Capital Variables						
Technical Assistance (% Yes)	Dichotomous	28%	-	-	-	-
Participation in Producer Organizations (% Yes)	Dichotomous	12%	-	-	-	-

3.3. Data Collection Technique

A semi-structured survey was designed, which included productive variables (farm area, crops, tree density, yields), socioeconomic variables (age, gender, education, membership in organizations, access to financing), technological variables (use of irrigation, soil analysis, technical assistance), and environmental variables (forest area, farm located in protected area). The questionnaire was administered in person by previously trained enumerators in both survey application and the use of the COMMCARE tool, and it was validated through a pilot test with 20 producers (Cisneros-Saguilán et al., 2023).

3.4. Study Variables and Operationalization

The variables were classified into three dimensions: social, economic-productive, and environmental, like studies on sustainability (Cobos Mora et al., 2021; Cáceres et al., 2023). Table 3 summarizes their conceptual definition, indicators, and measurement scale. For statistical analysis, continuous variables were transformed into standardized indicators before applying Principal Component Analysis (PCA), while categorical variables were processed through contingency tables and chi-square tests, as detailed by Chango Pilamunga et al. (2024) in their practical manual for SPSS. This procedure is essential for studies that aim to correlate the characteristics of groups or actors within a productive sector (Di Renzo et al.,

2020; Uquillas Granizo et al., 2025) (see Table 3). Data processing and statistical analyses, including PCA, K-means clustering, Kruskal-Wallis, and Dunn's post-hoc tests, were performed using Infostat 2020 and IBM SPSS Statistics, Version 22. Before conducting the PCA, all variables were standardized (Z-scores) to ensure that the analysis was based on correlation and not influenced by differences in scale or measurement units.

Table 3
Variables and Operationalization

Dimension	Variable	Conceptual definition	Indicators	Ítems/Values (Measurement Scale)
SOCIAL	Resident on the farm Farm located in a protected area	Condition of permanence or residence of the producer on the farm	Whether the producer resides on the property or not	1. Yes (Resident) / 2. No (Non-resident) (Nominal)
	Age Dependents Household members	Producer's age (in years) Number of household members Number of dependents	Years. Quantity	Numeric value in years. Number (Ratio/Discrete)
	Education Level	Highest level of formal education attained.	Last level of education completed.	1. No formal education / 2. Primary / 3. Secondary / 4. University (Ordinal)
	Organization	Formal participation in an association or cooperative of producers.	Membership in a producer organization	1. Yes / 2. No (Nominal)
ECONOMIC AND PRODUCTIVE	Agricultural area Forest área Without crops With rambutan With pastures	Area of the farm allocated to a specific land use or crop	Area in manzanas (1 Ha = 1.43 mzs)	Numeric value in manzanas (Ratio/Continuous)
	Crops type	Type of agricultural crops planted.	Names of crops planted.	1. Rambutan / 2. Coffee / 3. Citrus / 4. Other fruits / 5. Palm (Nominal)
	Production quantity	Total volume of the main harvest obtained.	Production weight per cycle	Numeric value in pounds or boxes (Ratio/Continuous, discrete)
	Form of sale	Mechanism or channel used to market the production	Distribution channel.	1. Direct to consumer / 2. Local intermediary / 3. Wholesaler / 4. El Salvador (Nominal)

Source: Authors' own elaboration

Dimension	Variable	Conceptual definition	Indicators	Ítems/Values (Measurement Scale)
	Selling price	Monetary value per unit of product at the time of sale.	Price per unit of measurement (kg, box, etc.)	Numeric value in local currency per unit (Ratio/Continuous)
ENVIRONMENTAL	Nursery on the farm	Existence of a structure or space dedicated to the germination and initial growth of seedlings.	Availability of a nursery.	1. Yes / 2. No (Nominal)
	Market Channel	Categoric (Ordinal)	Coded 1 (Local Intermediary), 2 (Regional Collector), 3 (Direct Wholesale), 4 (Export). Higher values indicate greater market integration.	
	Irrigation system	Use of infrastructure to supply water to crops	Has an irrigation system Type of irrigation infrastructure	Yes / No (Nominal) 1. Drip / 2. Sprinkler / 3. Channels / 4. None (Nominal)
	Pests and diseases	Identification of phytosanitary problems affecting production and their control	Yes / No (Nominal) Type of predominant pest or disease	Names of pests (Leafcutter ants, ants, birds, mealybugs) (Nominal)
	Performs crop association (intercropping)	Practice of rotating different types of crops in the same plot to improve soil quality	Does the farmer implement crop association?	1. Yes / 2. No (Nominal)
	Aplications	Frequency of agrochemical use (fertilizers or pesticides)	Number of applications per crop cycle	Numeric value of times (e.g., 3, 5, 8) (Ratio/Discrete)

Source: Authors' own elaboration

3.5 Data Analysis (Typification)

A Principal Component Analysis (PCA) with varimax rotation was applied to reduce data dimensionality and extract the main factors defining producer heterogeneity (Gómez Arce et al., 2025; García-Domínguez et al., 2021; Jaramillo-Villanueva et al., 2022). Prior to PCA, all continuous variables were standardized (Z-scores) to eliminate scale bias. A hierarchical cluster analysis was then conducted to determine the optimal number of groupings, followed by K-means clustering for final classification (Essary, 2022).Given that key continuous variables (farm area, income, and tree count) exhibited significant departures from normality (Shapiro-Wilk test, $p < 0.05$) and non-homogeneity of variance (Levene's test), non-parametric Kruskal-Wallis H tests were employed to assess differences across clusters (Souza et al., 2023; Hammel, 2005; González-Estrada et al., 2022). For statistically significant results, Dunn's post-hoc test with Bonferroni adjustment was used for pairwise comparisons. Categorical variables were evaluated using Chi-square (χ^2) and Fisher's exact tests where appropriate. All statistical analyses were executed using InfoStat (version 2020) and IBM SPSS Statistics (version 22)

4. Results

4.1. Producer Typology

The Principal Component Analysis (PCA) identified two main components that collectively explain 65.0% of the total variance (40.7% for Component 1 and 24.3% for Component 2), providing the foundation for the typology:

- **Axis 1 (Production Scale and Land Use)**: Explains **43% of the variance**. This axis strongly correlates with **scale variables** (total farm area, area dedicated to rambutan, number of trees) and **economic capacity** (annual income). This axis demarcates the **fundamental difference between subsistence/family farming and entrepreneurial agriculture** in Atlántida.
- **Axis 2 (Land Use Structure and Innovation)**: Associated with the proportion of forest and uncultivated areas versus specialization in rambutan. This factor captures the **diversification or specialization** of the producer and is indirectly linked to **technology adoption** (use of nurseries, soil analysis).

The clustering analysis (K-means) allowed for the classification of producers into three distinct typologies, confirming the structural heterogeneity.

Prior to the final analysis, the variable 'Use of Contracted Labor' was excluded from the factorial model due to consistency issues, as its strong correlation with income potentially inflated the clustering bias toward economic capacity. The final set of six variables was chosen to capture the core dimensions of scale, resource management, and social capital. Furthermore, to prevent the economic benefits of the bioeconomy from being captured exclusively by large-scale enterprises (Cluster 3), targeted policy interventions must intentionally foster collaborative networks. Specifically, intermediate producers (Cluster 2)—owing to their established organizational capital (39% participation)—represent the most viable vehicle to aggregate biomass (peels and seeds) from the vast base of smallholders (Cluster 1). By establishing cooperative pre-processing hubs managed collectively, the value-added residue can be processed locally

before reaching high-end nutraceutical or cosmetic markets, ensuring equitable wealth distribution across the territorial value chain.

As presented in Table 4, the final Principal Component Analysis (PCA) successfully identified two main components, which together account for 65.0% of the total variance in the data (40.7% for Component 1 and 24.3% for Component 2). This solution is statistically robust and satisfactory for the six variables analyzed. Component 1 (Physical-Economic Magnitude) is robustly defined by variables reflecting the scale and overall land capital of the producer. It is strongly associated with Total Farm Area (0.896), Forest Area (0.896), and Number of Rambutan Trees (0.708). The high loading of Forest Area on this component, alongside size variables, suggests that this factor primarily captures the total physical resource endowment (cultivated and non-cultivated land) that underpins the producer's scale, rather than just the cultivated area. Component 2 (Social and Technical Capital) is characterized by variables focused on strategic management and external access to resources. Its highest loadings are on Use of Soil Analysis/Technical Assistance (0.768) and Participation in Producer Organizations (0.754). This component effectively distinguishes producers based on their use of social and technical resources and their propensity for collective action and innovation. Communalities (h^2) are strong, ranging from 0.540 to 0.825, indicating that the two extracted components adequately represent the variance structure of the original variables, thus validating the factors used for the subsequent clustering analysis.

Table 4
Rotated Component Matrix and Variance Explained

Variable (Factor of Differentiation)	**Component 1 (Physical-Economic Magnitude)**	**Component 2 (Social and Technical Capital)**	**Communalities (h^2)**
Variables defining RC1 (Scale)			
Total Farm Area (ha)	0.896	0.091	0.817
Forest Area (ha)	0.896	-0.111	0.825
Number of Rambutan Trees	0.708	0.201	0.540
Annual Family Income (Lempiras)	0.575	0.502	0.582
Variables defining RC2 (Management)			
Use of Soil Analysis/Technical Assistance	0.171	0.768	0.619
Participation in Producer Organizations	0.244	0.754	0.627
Eigenvalue	2.439	1.460	3.899
Variance Explained (%)	40.7%	24.3%	65.0%

Source: Authors' calculations based on survey data (n = 314). Note: Loadings less than 0.30 are suppressed for clarity.

Figure 2 illustrates the spatial distribution of the producers based on the two extracted components. This projection confirms the structural robustness of the model, showing a dense concentration of Cluster 1 (Smallholders) near the origin, which reflects their limited scale and resource endowment. In contrast, Cluster 2 and Cluster 3 move distinctly along the management and physical capital axes, respectively, visually confirming the agrarian dualism present in the region.

4.2. Productive and Economic Characterization by Typology

As presented in Table 5, the three typologies differ significantly across their main productive and economic characteristics ($p < 0.001$), confirming a marked pattern of structural heterogeneity and agrarian dualism. The clusters are defined as follows:

- **Cluster 1 (Smallholders)**: Representing most of the sample (91%), this group operates with a median area of 1.7 ha and possesses the lowest capital and income, relying heavily on local intermediaries. This cluster faces severe structural constraints, including high barriers to investment and formal market integration.
- **Cluster 2 (Intermediate/Innovative Producers)**: Comprising 7% of the sample, this strategic group is clearly differentiated from Cluster 1. While operating on a moderate scale (median 7.1 ha), they demonstrate a transition toward commercialization, achieving a three-fold higher median income and adopting key organizational and technological practices.
- **Cluster 3 (Large Entrepreneurs)**: Accounting for 2% of the sample, this cluster dominates in scale and capital endowment. With a median area of 43.7 ha and high median income (Lps 290,000 / USD $11,685.59), these producers have direct access to export markets and the financial capacity to innovate independently.

Table 5
Producer Typologies and Key Differentiating Variables (N = 314)

Variable (Factor)	Overall Mean (N = 314)	Cluster 1: Smallholders (n = 285, 91%)	Cluster 2: Medium-Scale (n = 23, 7%)	Cluster 3: Large Entrepreneurs (n = 6, 2%)	Kruskal-Wallis Test (p-value)
Scale and Capital (RC1)					
Total Farm Area (ha)	6.09	3.80	40.50	73.50	p < 0.001***
Number of Rambutan Trees	466	322	1,522	3,185	p < 0.001***
Annual Family Income (USD dolar)****	3,891.03	2,821.20	10,259.22	15,991.25	p < 0.001***
Diversification and Resources (RC2)					
Forest Area (ha)	1.83	1.50	3.50	5.00	p < 0.01**
Technical Assistance (% Yes)	28%	20%	55%	75%	p < 0.001***
Participation in Producer Orgs. (% Yes)	12%	8%	39%	50%	p < 0.001***
Socioeconomic Indicators (Control)					
Average Age (Years)	54.0	55.2	48.5	45.0	0.07(n.s.)

Note: *p < 0.05; **p < 0.01; ***p < 0.001. Kruskal-Wallis test validates global differences between the three clusters, ****The exchange rate is 24.8469 Lempiras per US Dollar. Use of Contracted Labor' was excluded from the initial PCA to prevent capacity-bias collinearity; however, it is presented in this table as an auxiliary descriptive variable to illustrate structural differences across clusters.

The comparative profiles in Fig. 3 highlight the non-linear nature of producer differentiation. While Cluster 3 dominates in absolute physical scale, Fig. 3 reveals that Cluster 2 (Intermediate) possesses a strategic advantage in relative organisational capital and technical assistance adoption. This visual representation underscores that the transition from Cluster 1 to Cluster 2 is driven by management and social capital rather than mere land accumulation, a key finding for the Inclusive Rural Bioeconomy.

4.3. Socioeconomic, Technological, and Organizational Variables

Qualitative and structural indicators further reinforce the distinction among typologies ($p < 0.05$):

- **Organizational Participation**: Formal membership in associations or cooperatives is significantly higher in Cluster 2 (39%) compared to Cluster 1 (12%) and Cluster 3 (17%) ($\chi^2,\ p < 0.05$). Organizational capital represents the primary differentiating mechanism for intermediate producers, whereas smallholders operate individually and large entrepreneurs rely on private capital.
- **Technological Adoption**: Soil analysis and formal irrigation systems are concentrated in Cluster 3 (24% soil analysis) and Cluster 2 (10–14% irrigation and nurseries), while remaining virtually absent in Cluster 1, reflecting an innovation gap driven by investment capacity.
- **Commercialization Channels**: Local intermediaries absorb the majority of sales from Cluster 1. Conversely, Cluster 3 supplies wholesalers and exporters, while Cluster 2 leverages organizational coordination to secure formal sales channels and better prices.

To determine specific pairwise differences between clusters across these dimensions, Dunn's post-hoc test with Bonferroni adjustment was executed. As shown in Table 6, pairwise comparisons confirm significant differences between Cluster 3 and the other two groups in physical scale (Total Area and Trees, $p < 0.01$). However, Cluster 1 and Cluster 2 do not differ significantly in land size ($p = 0.082$) but exhibit a highly significant difference in Annual Family Income ($p < 0.01$) and Technical Assistance adoption ($p < 0.05$). This confirms that the transition from Cluster 1 to Cluster 2 is driven by management practices and organizational capital rather than land accumulation.

Table 6
Results of Dunn's Post-Hoc Pairwise Comparisons (Bonferroni Corrected)

Differentiating Variable	Cluster Pairwise Comparison (I vs J)	Adjusted p-value	Conclusion
Scale and Capital (RC1)			
Total Farm Area (ha)	Cluster 3 vs Cluster 1	**<0.001*** **	Significantly Different
	Cluster 3 vs Cluster 2	**<0.05* **	Significantly Different
	Cluster 2 vs Cluster 1	0.082 (n.s.)	No Significant Difference
Number of Rambutan Trees	Cluster 3 vs Cluster 1	**<0.001*** **	Significantly Different
	Cluster 3 vs Cluster 2	**<0.01** **	Significantly Different
	Cluster 2 vs Cluster 1	0.155 (n.s.)	No Significant Difference
Annual Family Income (The exchange rate is **24.8469 Lempiras per US Dollar.**)	Cluster 3 vs Cluster 1	**<0.001*** **	Significantly Different
	Cluster 3 vs Cluster 2	0.055 (n.s.)	No Strong Significant Difference
	Cluster 2 vs Cluster 1	**<0.01** **	Significantly Different
Diversification and Resources (RC2)			
Technical Assistance (% Yes)	Cluster 3 vs Cluster 1	**<0.01** **	Significantly Different
	Cluster 2 vs Cluster 1	**<0.05* **	Significantly Different
	Cluster 3 vs Cluster 2	0.520 (n.s.)	No Significant Difference

Note: *p < 0.05; **p < 0.01; *** p < 0.001. Dunn's test with Bonferroni correction for pairwise comparison of cluster means/medians.

The statistical evidence from the Dunn-Bonferroni post-hoc test (Table 6) confirms that the Honduran rambutan sector operates under a 'missing middle' structure. The lack of significant difference in farm area between Cluster 1 and Cluster 2 ($p = 0.082$), contrasted with their highly significant difference in income ($p < 0.01$), proves that productivity and economic resilience in Atlántida are decoupled from land size once a minimum threshold is met. This enlargement of results suggests that policy interventions should prioritise the 'organisational leap' observed in Cluster 2 to successfully integrate smallholders into higher value bioeconomic chains.

5. Discussion

The finding of three distinct typologies confirms a marked structural dualism, where a small entrepreneurial segment coexists with a large mass of subsistence producers. This outcome is highly consistent with the classical framework of structural heterogeneity proposed by Pinto (1970) and the analyses of rural poverty and policy in Latin America by de Janvry & Sadoulet (2000), underscoring that generalized development policies are ineffective. The existence of the three typologies empirically validates the marked structural heterogeneity of agriculture in Atlántida. However, our findings partially contradict the conventional optimistic view of some regional agricultural studies that assume high-value crops like rambutan automatically guarantee social mobility. As shown in our results, without a minimum threshold of organizational and technical capital, the crop's potential is insufficient to break the cycle of poverty in the most vulnerable segments.

5.1. Summary of the results and Theoretical implications

Cluster 1 (91% of producers) fits the profile of low-capitalized subsistence/family farming. Their limitations in scale, income, and technology adoption make them highly vulnerable to market volatility and climate change (Sánchez Toledano et al., 2023). The low resilience of Cluster 1 becomes a direct risk for rural depopulation and territorial marginalization. If rambutan—a high-value alternative crop—does not provide stable returns for this segment, the probability of intergenerational migration and the deterioration of the social fabric increase dramatically. The identified inequality is not merely economic but translates into a crisis of permanence in the territory (Duan et al., 2026; Di Mora et al., 2021; Martínez et al., 2020).

This study provides a significant advantage over previous descriptive studies by using a functional typology approach. While earlier research in the region focused on general yields, this study identifies how structural barriers specifically prevent the transition to a bioeconomy. The discussion focuses on how this structure affects territorial cohesion and the feasibility of an Inclusive Rural Bioeconomy (Corral et al., 2022; Henderson y Loreau, 2021). The descriptive statistics (Table 2) confirm the high dispersion and skewness of the economic variables, supporting the decision to use non-parametric tests (Kruskal-Wallis) and reinforcing the existence of structural heterogeneity.

5.2. Organizational Capital as an Agent of Change (Addressing Gaps)

Cluster 2 (Intermediate Producers) emerges as a strategic segment, notable for its higher organizational participation (39%) and its propensity for adoption of technology (Pradilla Cobos et al., 2022). This cluster acts as a critical hinge in the value chain, as its capacity for collective action overcomes the limitations of scale burdening Cluster 1. This result addresses the gap identified in Section 2 regarding how small-scale producers can survive in globalized markets: the answer lies in Organizational Capital.

The capacity to participate in the Circular Economy model (valorization of peels and seeds) is entirely mediated by this capital. Without collective action, the necessary investment for R&D and processing will be concentrated exclusively in Cluster 3, deepening inequality. The statistical differences found through

Dunn's post-hoc test (Table 6) solidify this dualism, proving that Cluster 2 is not just "larger" than Cluster 1, but fundamentally more organized and technically advanced.

5.3. Practical and Policy Implications

Rambutan's bioeconomic potential (valorization of peels and seeds for nutraceuticals/cosmetics) is a central finding (Mihai, 2023; Norton, 2022; Mercado et al., 2020). However, the Inclusive Rural Bioeconomy model must be intentionally inclusive to prevent benefit concentration (Zuniga-Gonzalez et al., 2024; Ronzon et al., 2022). Based on these findings, we propose the following differentiated policies:

For Cluster 1 and 2: Inclusion requires policies that prioritize investment in collective valorization platforms (e.g., collection and pre-processing centers operated by cooperatives). This anchors value addition to the territory, stabilizes incomes, and promotes the Inclusive Rural Bioeconomy as a local development strategy (Turcios Castro, 2023).

For Cluster 3 (Large Entrepreneurs): Policy must focus on environmental regulation and Corporate Social Responsibility (CSR), ensuring that their infrastructure innovations generate public goods accessible to the community.

A shortcoming in the application of these results is the cross-sectional nature of the data, which captures a specific moment in the production cycle. Additionally, while we identify the potential for waste valorization, the study does not account for the specific logistics costs of transport between dispersed smallholders, which remains a challenge for full practical implementation. Future research should include a Life Cycle Assessment (LCA) to fully quantify the environmental advantages of the proposed bioeconomic transition.

Furthermore, to prevent the economic benefits of the bioeconomy from being captured exclusively by large-scale enterprises (Cluster 3), targeted policy interventions must intentionally foster collaborative networks. Specifically, intermediate producers (Cluster 2)—owing to their established organizational capital (39% participation)—represent the most viable vehicle to aggregate biomass (peels and seeds) from the vast base of smallholders (Cluster 1). By establishing cooperative pre-processing hubs managed collectively, the value-added residue can be processed locally before reaching high-end nutraceutical or cosmetic markets, ensuring equitable wealth distribution across the territorial value chain.

6. Conclusions

This study demonstrates the marked structural heterogeneity of Nephelium lappaceum (rambutan) producers in Atlántida, Honduras, identifying three distinct typologies. Quantitatively, the results reveal a stark dualism: Cluster 1 represents the vast majority (91%) of producers with a median annual income of approximately $1,200, highlighting extreme economic vulnerability. In contrast, Cluster 3 (2%) controls 45% of the total productive area, confirming a highly concentrated value chain. Qualitatively, the findings identify Organizational Capital as the critical "hinge" variable. While Cluster 3 leads in scale, Cluster 2 (7%) serves as a strategic pivot, exhibiting the highest rates of organizational participation (39%) and technological

adoption. This suggests that the capacity to transition toward a bioeconomy is determined by the strength of collective action rather than land size alone.

The main conclusion is the inadequacy of "one-size-fits-all" public policies. Instead, a segmented approach is required to respond to the specific potential of each typology:

For Cluster 1 (Subsistence): Policy should prioritize the strengthening of Social and Organizational Capital through low-cost, specialized agricultural extension and flexible microcredit managed by local Cajas Rurales. The strategic goal is to increase formal credit access by 20% within three years to stabilize rural populations and mitigate migration risk.

For Cluster 2 (Intermediate): As the strategic agents of change, this group requires subsidies for quality certifications (e.g., GlobalGAP) and public investment in post-harvest innovation hubs and collection centers that can also serve Cluster 1.

For Cluster 3 (Large Entrepreneurs): Policy must focus on environmental accountability and Corporate Social Responsibility (CSR), encouraging the transfer of bioeconomic innovations—such as waste processing technology—to smaller producers.

Limitations and future research

Despite its contributions, this study has specific limitations. The research is based on cross-sectional data, providing a static "snapshot" that does not account for longitudinal fluctuations in international prices or climate-driven production cycles. Furthermore, the study does not include a full Life Cycle Assessment (LCA) or a detailed analysis of the logistical costs of transport between dispersed smallholders.

Future research should address these gaps by: (1) investigating the economic feasibility and minimum scale thresholds of cooperative processing models (peels and seeds) for Clusters 1 and 2; (2) evaluating the viability of Payment for Ecosystem Services (PES) as an incentive for sustainable practices in Cluster 1; and (3) mapping the relationship between the lack of Social Capital and intergenerational migration trends to ensure the long-term viability of the rural territory.

Declarations

Author Contribution

AUTHOR CONTRIBUTIONSConceptualization: AP-ÇG, CA-ZG Data curation: DA-MC, YM-MH, EF-OTFormal analysis: AP-ÇG, CA-ZG Investigation: AP-CG, CA-ZGMethodology: AP-CG, CA-ZGProject administration: AP-ÇG Resources: AP-CGSoftware: AP-CG, CA-ZGSupervision: AP-CG, CA-ZGValidation: AP-CG, CA-ZG Visualisation: AP-CG, CA-ZG Writing –original draft preparation: AP-CG, CA-ZG Writing –review and editing: AP-CG, CA-ZGAll authors have read and approved the final version of the manuscript.

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Data Availability

Data Availability Statement: The raw data supporting the findings of this article will be made available by the corresponding author, C.A. Zúniga-González, upon reasonable request, provided that institutional agreements with the National Autonomous University of Honduras and the National Autonomous University of Nicaragua, Leon are met (Colón-García et al., 2025).

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Figures

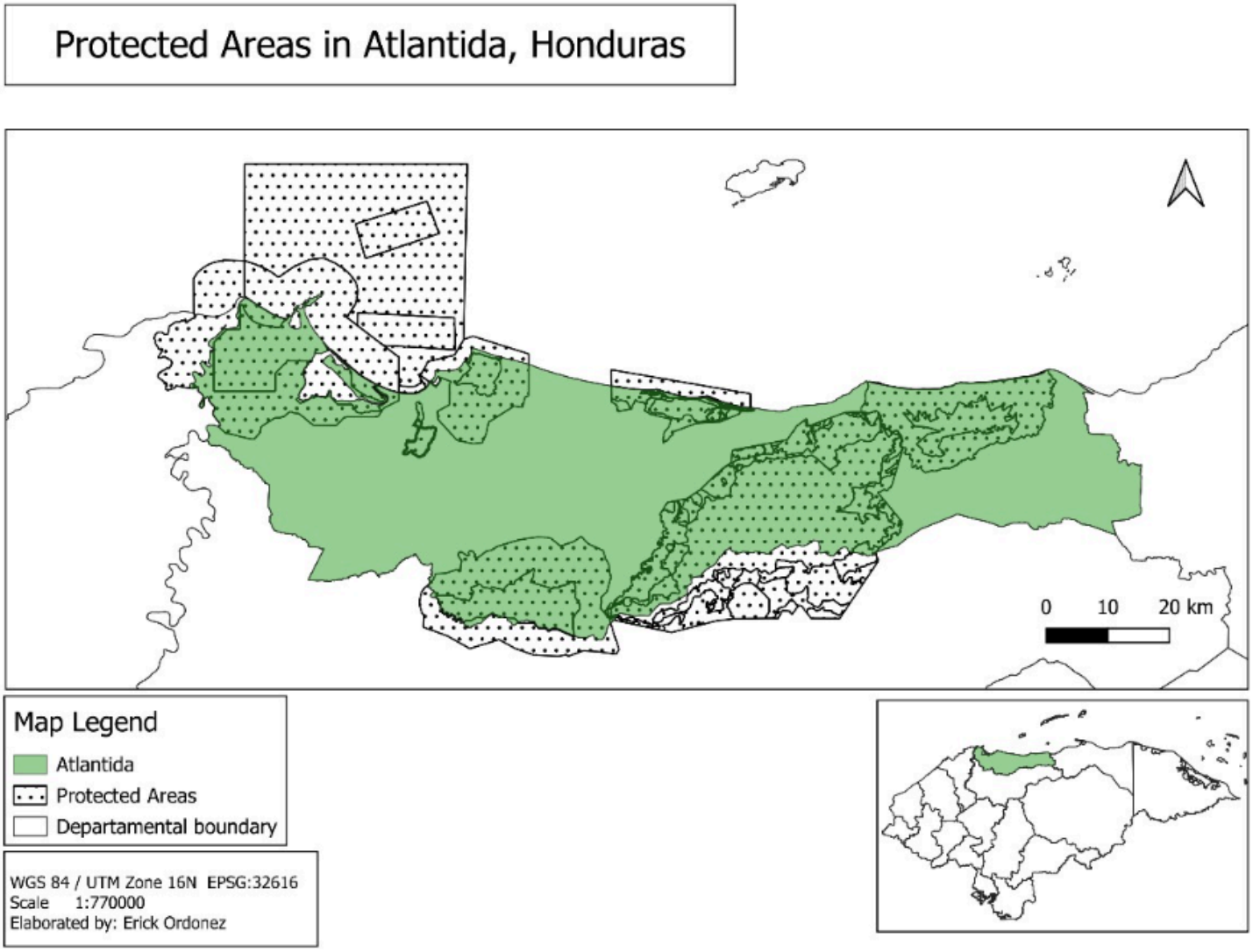


Figure 1

Study area map

Source: Own elaboration

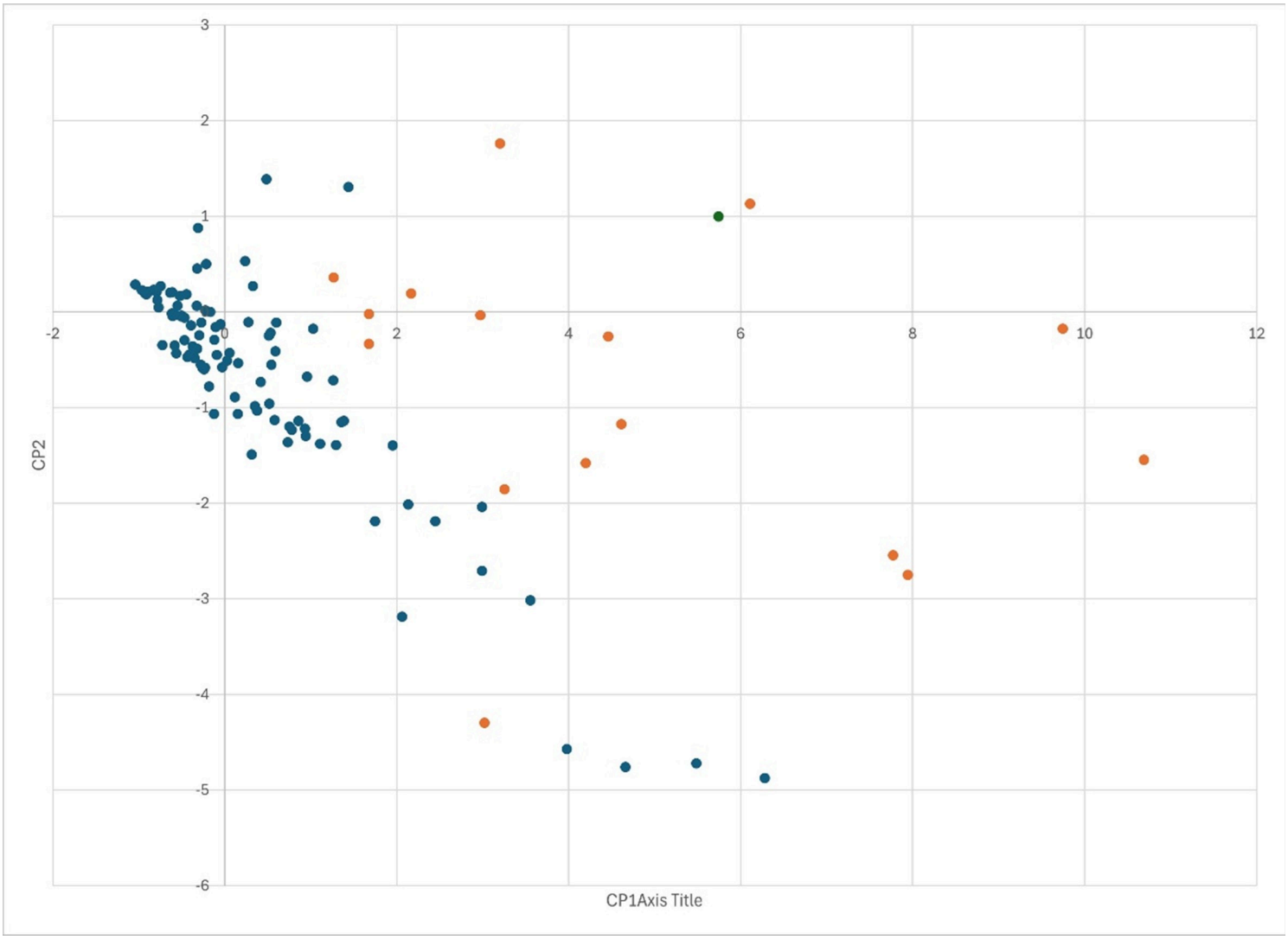


Figure 2

PCA Biplot of rambutan producers in Atlántida. Components 1 and 2 explain 65.0% of the total variance.

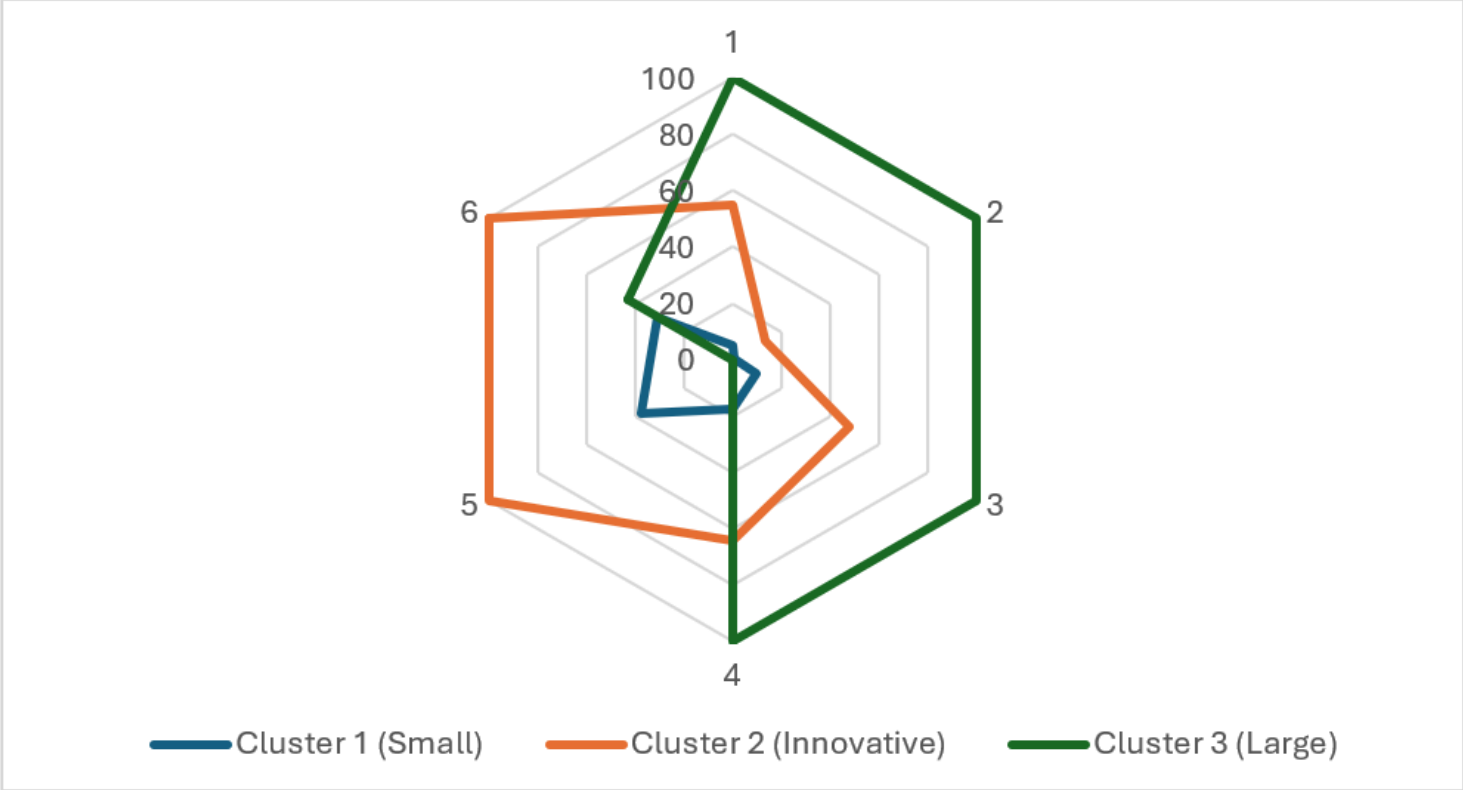


Figure 3

Comparative radar profile of producer typologies based on normalised structural and organisational variables.