

Modeling the Agricultural Supply Chain: Analysis of Statistical Dependencies in the Communities of Santa Elena, Ecuador

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Abstract

This study investigates the statistical relationship between the dimensions of production, inventory, marketing, and logistics in the agricultural supply chain of the Manglaralto parish, Santa Elena province, Ecuador. The objective is to identify the correlation between these dimensions and how they affect the efficiency of farmers, who suffer significant monetary losses due to poor infrastructure, training, and logistical organization. A mixed-method approach was used, through a survey of 336 farmers and a semi-structured interview with neighborhood leaders. The independence between 18 key variables was evaluated using nonparametric statistical tests: chi-square and Kendall's correlation. The results reveal that experience is independent of the cultivated area, while training is evidently related to marketing channels, and transportation quality and safety. In this way, it can be verified that logistics problems do not occur in isolation but rather derive from a combination of other factors. This contributes to local quantitative evidence and can be used for policy-making purposes to combine comprehensive actions to increase competitiveness and sustainability in agricultural development initiatives.

Keywords

Digital Innovation, Supply Chain, Statistical Relationship, Efficiency, Logistics

1. Introduction

The agricultural supply chain refers to a complex system made up of the set of activities, actors, resources, and information flows involved in the production, processing, storage, distribution, and marketing of agricultural products, from their acquisition and provision of inputs to their delivery to the final consumer [1]. In this sense, the agricultural supply chain goes beyond the mere sequence of logistical operations to encompass a series of economic, social, environmental, and technological aspects that influence the efficiency, sustainability, and resilience of global agriculture [2].

This consists of four basic dimensions: production, which also includes soil preparation, planting, crop management, and harvesting; inventory, including stock management, storage, and post-harvest handling; marketing, which generally involves market identification, pricing, and product negotiation; and finally, logistics, which includes transportation, distribution, information management, and coordination of key stakeholders [3].

On a global scale, the agricultural supply chain faces emerging challenges related to climate change, population growth, accelerated urbanization, evolving consumption patterns, and unstable international markets [4]. All these factors have increased pressure on agri-food systems to increase harvested quantities, reduce post-harvest losses, improve visibility, and ensure food security for a projected global

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population of approximately 9.7 billion people by 2050. FAO estimates that approximately one-third of global food production is lost or wasted at various stages of the supply chain, totaling 1.3 billion tons of food annually, valued at USD 936 billion [5].

In developed countries, losses are mainly found in the final stages of the chain, which are related to the high quality demanded, inadequate storage practices at home and retailers, and rejection based on appearance and external quality [6]. In the case of underdeveloped countries, such as those in Latin America and the Caribbean, losses accumulate in the initial and largely middle stages of the chain, given storage infrastructure problems, limited conservation technology, inadequate market access, transportation, and deficiencies in most of the chain, and the lack of coordination between actors Granillo-Macías, Rivera-Gómez, et al., [7]. This situation is even worse for small-scale agriculture, which represents around 80% of agriculture in Latin America and the Caribbean and supports more than 60 million people in the region.

In Mexico, factors associated with supply chain performance, such as product quality, processes, efficiency, flexibility, and customer/supplier relationships, influence overall performance. In line with Ortiz et al. [8] in their related study on factors associated with performance in agri-food supply chains in Mexico, this research sought to establish the interdependence of variables in terms of the performance of perishable products to meet the demand and competitiveness of the sector. It was possible to identify that the independent variables studied have a certain degree of correlation with supply chain performance. Therefore, the null hypothesis, which states that they are uncorrelated, was rejected. Therefore, all variables interact with each other to different degrees, but have a considerable impact within the sector, causing logistical problems within the different processes.

The Andean region, in particular, has witnessed significant transformations in its agri-food chains in recent decades. These transformations were driven by economic liberalization brought about by free trade agreements, greater development of urban demand, the expansion of supermarkets, and other factors. Along with the creation of new opportunities for direct market access for rural producers, new standards of quality, volume, consistency, traceability, etc., have emerged, which are not met by small farmers in the agri-food chain. The gap between market demands and the logistical capabilities of small producers has always determined rural exclusion in the region [9, 10].

Ecuador has implemented a set of public policies to strengthen agri-food chains, including the 2015-2025 National Agricultural Development Plan, the National Food and Nutrition Security Strategy, and the Participatory Rural Development Plan. In particular, the country has paid significant attention to road infrastructure, irrigation technologies, agricultural information systems, and technical assistance programs. However, review studies indicate that the impact is not evident in the most remote rural areas of Ecuador, especially in the Province of Santa Elena, where subsistence farming and weak supply chains have contributed little to the diversification of the local economy [11].

Santa Elena is a province on Ecuador's south-central coast with a unique set of geographic, climatic, and socioeconomic characteristics that combine to make it a particular hotspot for agricultural supply chain inefficiencies. With an area of 3,673 km² and a population of nearly 401,000, Santa Elena experiences high levels of multidimensional poverty, at 42.8% compared to the national average of 25.7% [12]. Therefore, Santa Elena is one of the five most vulnerable provinces in Ecuador. Its economy is traditionally diversified between artisanal fishing, sun and beach tourism, and small-scale rainfed agriculture focused on seasonal crops such as corn, beans, cassava, plantains, and vegetables [13].

Soil and climate conditions of Santa Elena, with less than 500 mm of annual precipitation and average temperatures above 24°C, the area classified as dry by Ecuadorians, impose significant restrictions on seasonal agriculture [14]. For this reason, producers in the province have to resort to irrigation systems that are often unavailable or inefficient. As a result, agricultural productivity in the province is very low, totaling 2.8 tons per hectare of staple crops. This rate is lower than the national Ecuadorian rate of 4.2 tons per hectare. Furthermore, the fragmentation of the agricultural market is also a significant issue, as 68% of productive units in the province are smaller than 5 hectares. As a result, efficient technologies are not used, and economies of scale are not realized.

The parish of Manglaralto in the canton of Santa Elena represents a microcosm of the challenges that small-scale agriculture in the province faces. It occupies a territory of 285 km² and encompasses

approximately 18,000 hectares, encompassing the communes of Barcelona, Dos Mangas, Curia, Sinchal, and Sitio Nuevo. More than 70% of households in these communes derive their livelihood from family farming. At the same time, farmers in Manglaralto face multiple structural barriers to accessing long-term and profitable markets.

Previous research in the parish identified several factors that contributed to the inefficiency of the supply chain in Manglaralto. These factors include a lack of storage centers that allow for a concentrated supply of agricultural products, a lack of appropriate post-harvest refrigeration facilities for the products to arrive, the presence of intermediaries who tax a substantial portion of the final margin, sources of information and price marketing for producers without access to information, and a precarious road in the parish that increases transportation costs and decreases the quality of the local product [15]. Post-harvest production losses currently represent 25% to 40% annually, with an economic value of more than US \$800, 000 per producer in the parish, depending on the crop and the season.

For this reason, the underlying causes of all these inefficiencies are numerous and interconnected. On the one hand, there is a lack of coordination among the various actors in the chain—producers, transporters, marketers, and government institutions—which leads to duplication of efforts, a lack of process standardization, and a lack of opportunities for synergy. On the other hand, public investment in adequate rural infrastructure has been scarce, especially with regard to rural roads, collection centers, and water systems. This limits agricultural producers' ability to scale their operations and access more attractive and lucrative markets.

The study addresses critical problems faced by agricultural producers in Manglaralto Parish, Santa Elena Province, related to production, storage, marketing, and logistics. Logistical issues such as poor inventory management, inefficient channel distribution, and suboptimal transportation and distribution modes cloud farmers' judgment in effectively processing and selling their produce. The lack of a comprehensive, systematic approach to these problems will result in the expiration of product freshness and quality, increased operating costs, delayed delivery times, and a reduction in the initial competitiveness of agricultural products. All of these inefficiencies are resulting in massive financial losses for farmers, jeopardizing the viability and sustainability of their operations.

In this context, the purpose of this research is to provide a comprehensive analysis of the statistical relationship between production, storage, marketing, and logistics throughout the agricultural sector of the parish of Manglaralto, province of Santa Elena, Ecuador. By quantifying the crucial relationships between these components of the agricultural value chain, quantitative evidence will reveal how these factors interact with each other in the operational and competitive efficiency of producers in the region. By understanding the nature of the relationship between these factors, targeted responses can be developed to improve agricultural management, profitability, and the sustainability of agricultural operations in Manglaralto. This provides a platform for the creation of direct policies and specific solutions at the local level.

2. Methods

The research was conducted using qualitative and quantitative methods, using a mixed approach that allowed for a comprehensive understanding of the relationships between production, inventory, marketing, and logistics in the Ecuadorian parish of Manglaralto, province of Santa Elena. The study followed ethical standards for research involving human subjects; consequently, all participants provided informed consent before completing the questionnaire, and all data were processed anonymously to ensure confidentiality. As a non-experimental study, the methodology focused on descriptive, exploratory, and literature review methods.

Data collection was based on a semi-structured interview with leaders of agricultural associations and a self-assessment survey of 336 farmers, with the largest sample representing the communities of Barcelona, Dos Mangas, Curia, Sinchal, and Sitio Nuevo. The results are subject to triangulation given the variability obtained at a 95% confidence level and a 5% margin of error. Validity and reliability were verified and assessed with Cronbach's alpha coefficient, which yielded a result of 0.763, proving the

consistency of the questions.

For data analysis, statistical tests such as chi-square and correlation analysis were used to assess the relationships and dependencies between the four key dimensions: production, inventory, marketing, and logistics. This approach allowed us to identify significant patterns and connections between these variables, providing a clear view of how they interact with each other and how these interactions affect the operational efficiency and competitiveness of agricultural producers in the region.

Data analysis included statistical tests such as chi-square and correlation analysis, which were used to verify the relationships and dependencies between the four key dimensions previously discussed: production, inventory, marketing, and logistics. This method revealed certain significant patterns and links between these variables and provided insight into their interconnectedness and how they influence the efficiency and productivity of agricultural producers in the region.

3. Results

Due to the qualitative nature of the data, nonparametric statistics were applied for correlation and independence analysis. For the former, Kendall's tau was used, which confirms the independence or dependence of the group of variables analyzed, while for the latter, the chi-square test was applied. The following table shows the 18 variables investigated with their assigned codes, applied in the instrument. These investigated variables were grouped into four dimensions, as shown below:

Table 1
Coding of study variables.

Production		Inventory		Marketing		Logistics	
Cod	Variable	Cod	Variable	Cod	Variable	Cod	Variable
P 3	Experience	P8	Inventory	P10	Channels	P14	Transport
P5	Area	P15	Infrastructure	P11	Intermediaries	P16	Actors in the process
P6	Products	P22.1	Available infrastructure	P12	Prices	P22.2	Quality of transport
P7	Production time			P19	Training topics	P22.3	Transport security
P17	Challenges			P22.5	Distribution channels	P22.4	Access routes

Independence test

1. Hypothesis Test:

- H0: The data are independent.
- H1: The data are not independent.

2. Level of significance: $\alpha = 0.05$

3. Test statistic: Equation 2-3: Chi-Square

$$x^2 = \sum_{i=1}^k \frac{(O_i - E_i)^2}{E_i} \quad (1)$$

4. Decision rule: if $P > \alpha$ H_0 not rejected.

3.1. Statistical Analysis by Dimensions

3.1.1. Production Dimension: Independence and Correlation Analysis

Table 2 presents the results of chi-square tests between pairs of categorical variables related to agricultural activity. The table reflects the strongest relationship found between the length of time farmers

have been farming (P3) and the area they farm (P5), with variation ($\chi^2 = 27.97$, $p = 0.0056$); the results indicate that as the number of years they have been farming increases, so does the area they farm. However, there is no relationship between years of experience and the type of crops they grow ($p = 0.203$). However, there is a strong relationship between length of experience and the most productive dates, with a chi-square of 48.85 and a p-value of 2.23×10^{-6} , suggesting that "time" is also a concept associated with seasonal patterns. The relationship with the main production problems is also significant, with a chi-square of 35.82 and a p of 0.016, suggesting that the length of experience also affects this aspect. However, there is no evidence of associations between the size of the cultivated area and the three remaining groups of variables, since $p > 0.05$. The relationship between cultivated products and production problems, p -value = 6.41×10^{-9} , is highly significant, suggesting that the products and problems are related in the way they are associated. Overall, this chi-square matrix reflects how the connected variables influence each other in different ways.

Table 2

Decision Rule - Production.

Variable1	Variable2	χ^2	p_value	Rejection_H0
P3	P5	27.97120637	0.005585953	They are dependent
P3	P6	15.74901049	0.203004173	They are independent
P3	P7	48.84634881	2.22512E-06	They are dependent
P3	P17	35.81947407	0.01614973	They are dependent
P5	P6	2.929086467	0.96704012	They are independent
P5	P7	21.33874603	0.01122836	They are dependent
P5	P17	11.39161312	0.724371897	They are independent
P6	P7	2.223885741	0.987412197	They are independent
P6	P17	69.1180739	6.41077E-09	They are dependent
P7	P17	24.31316714	0.059962645	They are independent

Figure 1 shows the production variables (P3, P5, P6, P7, and P17), with their correlation coefficients for each pair of variables. The diagrams allow estimating the interdependence and magnitude of the factors' influence that define the strength of dependence. As observed, the correlation coefficients range from -0.102 to 0.103, indicating a weak relationship between experience in agriculture. The strongest correlation, albeit weak, is between P6 and P7 (0.103), which shows this broad trend in seasonally grown products. On the other hand, the negative correlation between P5 and P17 (-0.102) implies that the larger the cultivated area, the more challenging it is. Furthermore, the correlations are close to zero, meaning that individual factors are neither good nor bad values for significant components of performance measures in agricultural production.

3.1.2. Inventory Dimension: Independence and Correlation Analysis

In the Chi-square test in Table 3, the relationship between variables P8 and P15 has a value of 11.2461 and a p-value of 0.0467. Since $0.0467 < 0.05$, the variables are essentially significant, making them dependent. This result indicates that there is a correlation between the two variables and that one of them affects the behavior of the other. Similarly, the relationship between P8 and P22.1 is significant. This is calculated as $X^2 = 7.49$ and $p = 0.0236$. Therefore, the two variables are dependent. This test highlights a relationship between the two variables, which can be admitted to exist and is not causal. The X^2 value for the dependent variables P15 and P22.1 is 17.69, and the p-value is 0.0604. Although this dependence is the weakest among all, it is close to the lower level used in this test. It can be seen that the null hypothesis of independence has not been rejected, so the relationship between P15 and P22.1 does not pass the significance threshold. These findings point to sensitive relationships between variables in this dimension that can affect how the associated processes are managed and optimized.

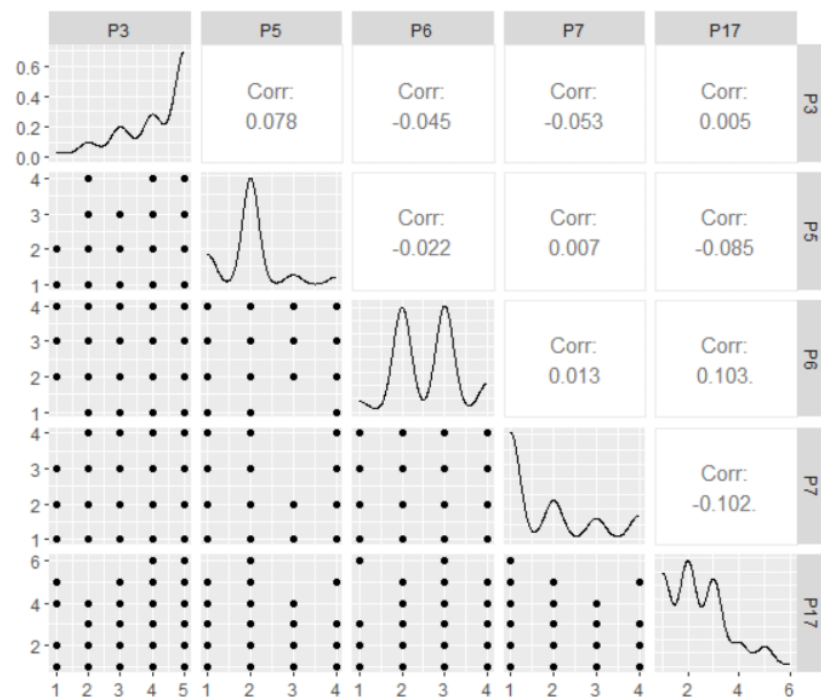


Figure 1: Correlation graph – Production.

Table 3

Decision Rule - Inventory.

Variable1	Variable2	χ^2	p_value	Rejection_H0
P8	P15	11.24610809	0.046712926	They are dependent
P8	P22.1	7.491902296	0.023613159	They are dependent
P15	P22.1	17.69047794	0.06041476	They are independent

Figure 2 shows the dispersion of the inventory variables along with the phases (P8, P15, and P22.1), revealing the strength and direction of the interrelationships between these variables. The figure shows a slight positive correlation between P8 and P15 (correlation factor of 0.076). This suggests that infrastructure improvements may have a slight positive effect on inventory management. However, the correlation coefficient between P8 and P22.1 is almost zero (-0.003), suggesting that existing infrastructure has little direct effect on inventory levels. Furthermore, the correlation coefficient between P15 and P22.1 is equal to -0.090. Therefore, these correlations show that the relationship between inventory management and infrastructure variables is highly complex and limited, indicating that these direct factors also affect inventory.

3.1.3. Marketing Dimension: Independence and Correlation Analysis

In terms of marketing, it can be observed that the variables P10 and P19 are dependent. According to the Chi-square data, there is a statistically significant relationship between these two since the p_value is 5.98×10^{-8} . Given this, according to the market, P10 and P19 are highly dependent on each other, meaning that any change in one of them will affect the other. Likewise, P11, P19, P12 and P19 are also related to each other, since $X^2 = 10.72$ with p_value = 0.0299 and $X^2 = 27.74$ with p-value = 0.0339. In conclusion, P19 is also related to many other variables of consideration in terms of the market, unlike P10-P11, P10-P12, P10-P22.5, and P11-P22.5, which are independent $p > 0.05$. This means that there are no statistically significant relationships between these pairs of variables; consequently, they are more

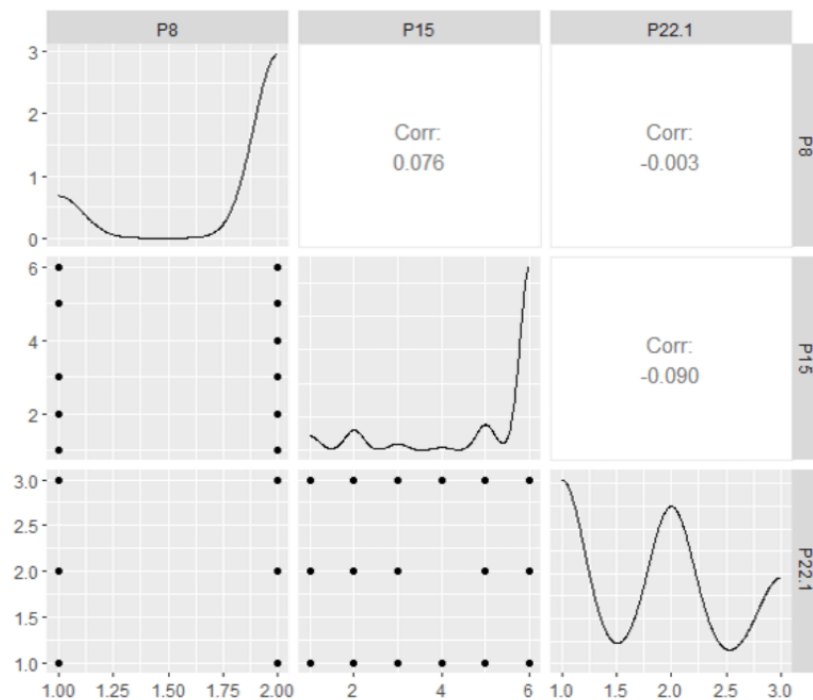


Figure 2: Correlation chart - Inventory.

independent in the marketing process. Finally, P19 and P22.5 are also dependent ($X^2 = 30.33$, $p\text{-value} = 0.0164$).

Table 4

Decision Rule - Marketing.

Variable1	Variable2	χ^2	p_value	Rejection_H0
P10	P11	3.111162902	0.874531789	They are independent
P10	P12	28.67550696	0.429121489	They are independent
P10	P19	86.90935728	5.98261E-08	They are dependent
P10	P22.5	32.93688015	0.238076514	They are independent
P11	P12	31.09955701	2.92152E-06	They are dependent
P11	P19	10.71890913	0.029911509	They are dependent
P11	P22.5	5.781440586	0.216075804	They are independent
P12	P19	27.74079985	0.03394802	They are dependent
P12	P22.5	8.809772031	0.921040055	They are independent
P19	P22.5	30.32878139	0.016370232	They are dependent

Prepared by: The authors

Figure 3 shows the dispersion matrix for the marketing variables (P10, P11, P12, P19, and P22.5). The most representative correlation is between P10 and P19 (-0.158^{**}), showing a moderate and negative correlation, implying that as marketing channels increase, training rates decrease. Furthermore, P11 and P19 (-0.094) also show a negative, albeit weak, association, which may suggest that intermediary links in the marketing chain have little influence on farmer training. On the other hand, P10 and P22.5 (0.101) and P19 and P22.5 (-0.140^{*}) show moderate positive and negative correlations, respectively, suggesting that the way channels are distributed and the training topics may influence marketing

channel efficiency.

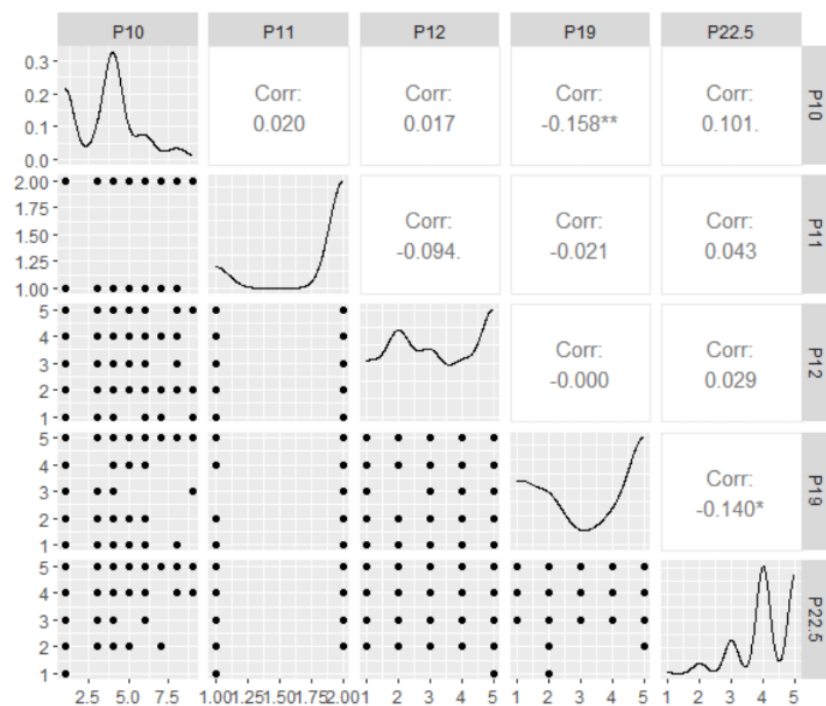


Figure 3: Correlation Chart – Marketing.

3.1.4. Logistics Dimension: Independence and Correlation Analysis

In Table 5, the dependence of variables in logistics manifests, P14 and P22.2 ($X^2 = 28.77$, $p_values = 0.0172$), P14 and P22.3 ($X^2 = 52.47$, $p_values = 9.71e-05$), which are interdependent variables in the sense of logistic context. That is, there is a direct interaction of P 14 in the appearance of P22.2 and P22.3, and vice versa. And the variable P16 depends on the variable P22.3 ($X^2 = 41.51$, $p_value = 0.0146$) and the variable P22.4 ($X^2 = 48.68$, $p_values = 2.38e-06$). In other words, these relationships are also shown by the dependence in this logistic regression study. On the other hand, in our interpretation, the relationships between P14 and P16 and between P14 and P22.4 are independent. That is, the probability of being significantly related is 0.05. In other words, they are not interrelated. This means that even though P16 is a significant predictor of P14, it is not necessary for its fulfillment. The dependence between P22.2 and P22.3 ($X^2 = 113.36$, $p_values = 1.29e-18$) is necessary. It often means that one alone can do the other is extremely high in logistics. The interdependence of P22.2 and P22.3 means that one cannot be done without the other. And finally, the association between P22.3 and P22.4 is also dependent ($X^2 = 21.53$, $p_value = 0.0059$).

In Figure 4, the scatter plot matrix for the logistics variables (P14, P16, P22.2, P22.3, and P22.4) presents how these are correlated, which are in the range of -0.152^{**} to 0.164^{**} , indicating moderately strong associations between some variables. In other words, P16 and P22.3 are positively related at a moderate level (0.164), indicating that the participation of actors in the logistics process can be associated with transportation safety. Conversely, P16 and P22.4 are negatively related at a moderate level (-0.152^{*}), which could indicate that better access infrastructure (communication routes) reduces the number of actors involved in the logistics process. These interrelationships highlight the need for integrated logistics management that considers safety, transportation efficiency, distribution, and the interdependencies between the elements of the logistics system.

Table 5
Decision Rule - Logistics.

Variable1	Variable2	χ^2	p_value	Rejection_H0
P14	P16	42.19669018	0.068844064	They are independent
P14	P22.2	28.77261329	0.017203777	They are dependent
P14	P22.3	52.47420313	9.70708E-05	They are dependent
P14	P22.4	4.627013243	0.914662455	They are independent
P16	P22.2	22.31743579	0.218196428	They are independent
P16	P22.3	41.51494735	0.014614943	They are dependent
P16	P22.4	48.68103208	2.37809E-06	They are dependent
P22.2	P22.3	113.363927	1.29034E-18	They are dependent
P22.2	P22.4	12.43973965	0.052847717	They are independent

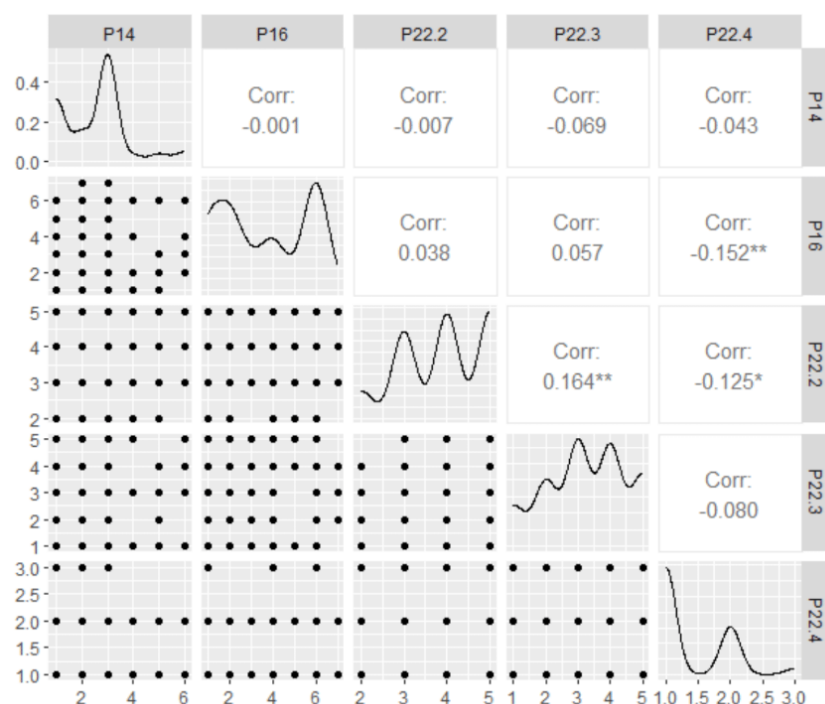


Figure 4: Correlation chart - Logistics.

4. Discussion

The results obtained in this study advance our understanding of the relationships between key dimensions of the agricultural supply chain in the parish of Manglaralto, province of Santa Elena. Statistical analysis reveals significant dependencies between production, inventory, marketing, and logistics variables, suggesting that efficiency problems in the supply chain are not independent, but rather the result of the interaction of multiple factors.

In the production dimension, farmers' experience (P3) is found to support the area under cultivation (P5), production time (P7), and challenges faced (P17). These known relationships could present a pattern indicating the importance of experience in yield. However, these variables are independent in Manglaralto.

Regarding inventory, the amount of stored product (P8) is counterbalanced by the available infrastructure (P15 and P22.1). This relationship clarifies the assertion that the lack or neglect of infrastructure

is insufficient for the storage and preservation of agricultural products; it is one of the most critical limiting factors for the effectiveness of inventory management in the region. The correlation, although weak, is positive, implying that even small improvements in infrastructure could lead to increased storage and, therefore, a reduction in post-harvest losses.

Regarding marketing, training (P19) appears to encourage its use or relationship with the use of marketing channels (P10); with the participation of intermediaries (P11); prices (P12); and storage and distribution channels (P22.5). This significant relationship implies that farmers who have received training incorporate more information regarding price and demand and the use of retail commercial channels. There is a negative correlation with the type of marketing channel relationships, which implies that trained producers may need intermediaries less and can make prices more accessible to consumers.

Regarding logistics, many significant dependencies were found between transport conditions (P14), transport quality (P22.2), transport safety (P22.3), and accessibility (P22.4). These results confirm the hypothesis of the importance of infrastructure and transport conditions for the quality and timeliness of agricultural product supply. The strong relationship between transport quality and safety indicates that both aspects should be considered simultaneously to achieve effective improvements in food logistics.

These results are aligned with the study conducted under different conditions and in a relatively similar context by Ortiz et al. [8], who found in their study of the agricultural product system in Mexico that variables corresponding to product quality, process efficiency, operational flexibility, and customer-supplier relationship processes. Also, as in the case of Manglaralto, these variables are not isolated and are all correlated with each other, creating an additive value in competitiveness.

In summary, the findings of this study are consistent with previous literature in that small-scale food supply chain systems suffer from systemic factors that require systematic interventions. According to FAO [3] and Torres Reyes [15], a lack of coordination among actors, limited investment in infrastructure, and a lack of technical training are systemic factors that affect supply chain efficiency. Furthermore, improving a single dimension is insufficient to significantly impact producers' competitiveness given the interdependence of the variables analyzed.

However, the research generated local evidence that can be used to guide and calibrate interventions and public policies to improve food chains in Manglaralto. Therefore, the promotion of technical training programs that integrate production and commercial aspects, as well as investment in storage and transportation infrastructure, is recommended.

5. Conclusion

It is demonstrated that the dimensions of production, inventory, marketing, and logistics in the Manglaralto supply chain are actually statistically related to each other. Therefore, all supply chain issues must be addressed together, not in isolation. Furthermore, the dependencies between key variables found in this study suggest that actions should also be integrated. Through dependency and correlation, it is evident that producer experience, infrastructure, training, and transportation are highly correlated. Together, they influence efficiency and competitiveness.

It is stated that the general hypothesis formulated at the beginning of the study is accepted: there is a statistically significant dependence between production, inventory, marketing, and logistics dimensions within the agricultural supply chain in Manglaralto. This is based on several χ^2 values with $p < 0.05$ obtained in the independence tests, as well as on the correlation coefficients showing the variables' connecting factors.

In addition to confirming the hypothesis regarding the relationship between the dimensions studied, this research quantifies the nature and relative magnitude of these relationships, which allows for more technical elements for decision-making. By linking these variables to impact measurements, the qualitative diagnosis now becomes a metric understanding of the problems, based on which public policies, rural development programs, or even private investments can be designed that directly address the problems we identified.

Declaration on Generative AI

The authors did not use GenAI during the preparation of this work. The authors reviewed and edited the content as necessary and assume full responsibility for the content of the publication.

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