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Typology of Production Units for Improving Banana Agronomic Management in Ecuador

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Abstract: Ecuador is one of the world's leading banana exporters; however, low productivity resulting from inadequate agronomic management requires an analysis of banana production units. This study aimed to define the types of banana production units based on the different agronomic management practices adopted by producers in two Ecuadorian provinces. Data from the National Institute of Statistics and Censuses (INEC) for 2021 were used, with a sample of 319 production units. Principal component and cluster analyses were applied to identify the different types of production units, resulting in four types: high technology conventional (Cluster 1), balanced conventional (Cluster 2), intensive conventional (Cluster 3), and agroecological (Cluster 4). It is important to highlight that 58% of the production units are intensive conventional and use an average of 3.5 management practices, with 98% using fertilizers, 100% using fungicides and pesticides, and 45% using improved genotypes. In contrast, agroecological production is still incipient in Ecuador (4.7%). Regression analysis showed that waste is important in high-yield production units in the three clusters. In addition, Cluster 2 relied on regional factors, family labor, and irrigation efficiency, while in intensive conventional farms (Cluster 3), banana yield was related to fungicide application. Therefore, public policies should be customized according to cluster-specific characteristics to optimize agronomic management practices and facilitate their transfer among groups.

Keywords: cluster analysis; data analytics; multiple regression; *Musa paradisiaca*; principal component analysis

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1. Introduction

Agriculture in Ecuador plays an important role in food security, poverty reduction, economic development, and resource generation [1,2]. In the coastal lowlands, agriculture is carried out by small and large producers and is concentrated near the river basins [3]. In this region, agricultural activities are favored by geographical and climatic factors (i.e., tropical climate, fertile soils, irrigation potential, and export access), with crops such as bananas, cocoa, rice, corn, soybeans, sugarcane, and African palms [4]. Among these crops, bananas are the most economically important agricultural product in Ecuador, accounting for around 35% of the country's agricultural GDP [5]. They are also the crop with the greatest technification, involving irrigation, precision application of fertilizers and pesticides, and biological control methods [6,7].

The provinces of Guayas and Los Ríos are where bananas are traditionally grown [8]. According to the 2022 agricultural census, the production of bananas in the Guayas and Los Ríos provinces accounted for 431 Mg and 351 Mg, respectively [9]. Collectively, these two provinces account for 70% of the total production in Ecuador, as indicated by Ortiz-Ulloa et al. [10]. The favorable local conditions, including temperature, rainfall distribution, and fertile soils, make these provinces suitable for banana cultivation [11]. However, there is significant variation in yields between production units [12]. Moreover, there has been a decrease in yields over the past five years [9]. It is important to note that when comparing production per unit area with Central American countries, Ecuador's yield values are relatively low [13]. These low yields are primarily linked to fungal diseases affecting the roots of the plants [14].

In this context, this may be attributed to inadequate farming practices: improper fertilization, insufficient use of pesticides to combat pests and diseases, and the quality of the genetic material [14–16]. Research aimed at enhancing the agronomic management of the banana is limited. For example, Villaseñor-Ortiz et al. [6] developed a tool to determine the optimal levels of potassium and nitrogen fertilization through the analysis of leaf data from commonly grown varieties in Ecuador, but further modifications are necessary before it can be implemented in the field. Separately, Veneziano et al. [17] investigated Carbendazim residues in bananas from Ecuador, Panama, and Costa Rica and discovered that 5% of the samples studied exceeded the permissible limits for this chemical compound. Clearly, these inadequate practices have detrimental effects on yield, economic income, and health [18,19].

The primary approaches for cultivating top-quality bananas are promoted by numerous agricultural extension organizations. These include, first and foremost, the implementation of genetic material that exhibits resistance to diseases and pests [20] and the integration of diverse irrigation techniques on all banana farms [21]. Moreover, the government, private sector, and farmers are vigilant in efforts to prevent the introduction of new diseases, such as the fungal pathogen *Fusarium oxysporum* tropical race 4, which is already present in the neighboring countries of Venezuela, Colombia, and Peru [22].

Despite the programs and initiatives of different organizations to improve the agronomic management of bananas, little research has been carried out to adopt these technologies. The diversification of techniques can benefit both banana yields and economic income, regardless of the size of the production unit [23,24]. This diversification of techniques can be known and applied if there is technology transfer between farmer groups and extension services, private companies, and government agencies [25].

In previous studies, in order to establish different types of agricultural production units of different species (peppers, sugar cane, melons, and rice), socioeconomic variables were included together with different agronomic management [26,27]. Thus, this typology could help in the implementation of robust public policies to increase the yield per unit area of the banana plant.

The objective of the present work was to define types of banana production units based on different agronomic management practices adopted by producers in two provinces of Ecuador. The specific objectives were: (i) to explore the variation between production units in the adoption of different banana management practices; (ii) to identify relevant management practices adopted by the different groups of producers through principal component analysis and cluster analysis; and (iii) to analyze the variation in yield, access to agricultural extension services, knowledge, socioeconomic characteristics, and agronomic attributes of each group.

2. Materials and Methods

In this study, the adoption of various management practices and technologies linked to banana production and property types was examined. First, the characteristics of the properties and types of management in this crop were obtained through a literature review and discussion with technicians from the private and public sectors [28,29]. In the second step, data from the 'National Agricultural Census' conducted by Ecuador's National Institute of Statistics and Censuses (INEC) in 2021 were evaluated for quality and adequacy. In the third step, the processed data were analyzed using Principal Component Analysis (PCA) and Cluster Analysis (CA) to identify homogeneous groups according to the technologies used in crop management. Finally, multiple linear regression (MLR) analysis was performed for each cluster to identify significant explanatory variables for yield (Mg of banana per ha) rather than for prediction.

2.1. Study Area and Data Formatting

Since 2015, the INEC has utilized a semi-structured survey at the national level to gather data on social, technological, and income factors for both agricultural and livestock products (ESPAC). INEC divided the country into segments, defined as squares of land between 0.1 and 5.8 square kilometers. The size of each segment is determined by the intensity of agricultural production in the area, and these segments are characterized by homogeneous agroecological conditions [30]. The permanent crops section of the survey includes information on the banana plant, as well as 80 other species.

The provinces of Guayas and Los Ríos (Figure 1) were selected for this study due to their significant planted areas and high number of producers [11]. Both provinces are situated in Ecuador's coastal region and have comparable geographical and climatological conditions. The altitude in these provinces ranges from 5 to 50 m above sea level, and, according to the Koppen classification system, they fall within the tropical savannah agroecological zone (Af) [31]. The average annual rainfall in these provinces is 2208 mm, with most precipitation occurring between January and May and in December [32]. The primary soil types in both provinces are vertisols, alfisols, and entisols, with variable textures [33].

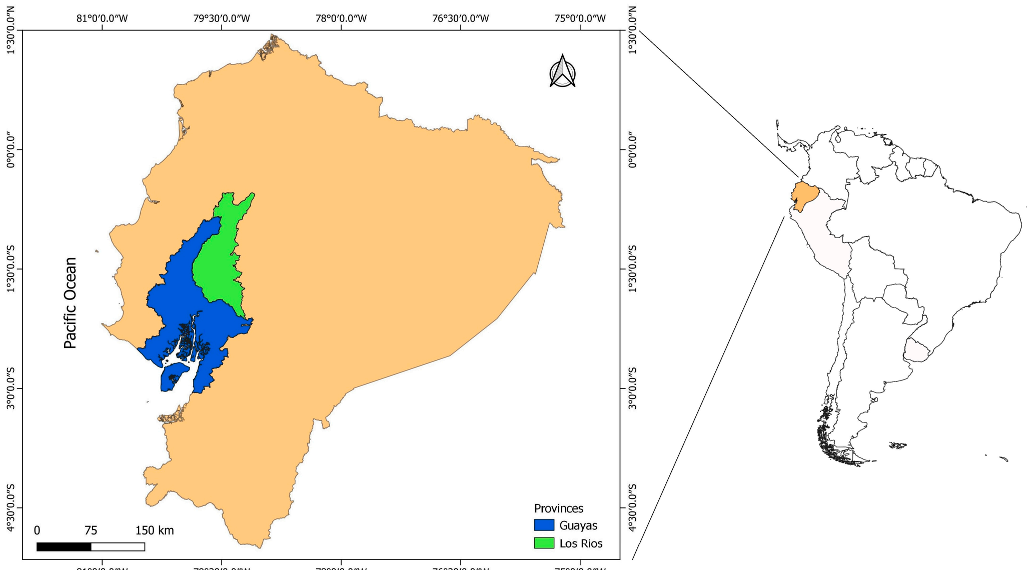

Figure 1. Geographical location of the Ecuadorian provinces included in this study.

The original spreadsheet is open for consultation and can be viewed on the website https://www.ecuadorencifras.gob.ec/estadisticas-agropecuarias-2/, accessed on 3 January 2023. In the survey, the variables described above were expressed per production unit. Thus, the variables that were created/modified based on the information of the original spreadsheet were yield (Mg ha^{-1}), waste (Mg ha^{-1}), and quantities (kg ha^{-1} or L ha^{-1}) of the variables: fertilizer, pesticide, fungicide, and organic inputs. In addition, as all the production units had irrigation, the irrigation efficiency was calculated for the systems used (furrows, sprinklers, micro-sprinklers, and drip irrigation) using the values proposed by Mantovani [34].

After all the variables were created, exploratory data analysis was carried out. Outliers (by productive unit) were eliminated, especially blank spaces for the yield. These production units were likely in the non-productive phase (production units removed: 21). In total, 319 productive units were included in the analysis: 150 properties in Los Rios and 169 properties in Guayas. Ecuador is divided into provinces, cantons, parishes, and neighborhoods. In addition, the information used and the characteristics of each variable are shown in Table 1. The Section 2.2 details the crop management variables used to create the clusters.

Table 1. Description of the variables, units, and minimum and maximum values of the variables used for the principal component analysis and cluster analysis and the subsequent variables included to characterize the types of production units.

Variable	Description and Units	Minimum	Maximum
Agronomic managements			
Use of fertilizer	=1 if mineral fertilizers are used. 0 if mineral fertilizers are not used.	0	1
Use of organic inputs	=1 if organic inputs are used. 0 if organic inputs are not used.	0	1
Use of fungicides	=1 if fungicides are used. 0 if fungicides are not used.	0	1
Use of pesticides	=1 if pesticides are used. 0 if pesticides are not used.	0	1
Plant density	=1 if high density is used. 0 if low density is used.	0	1
Use of improved genotypes	=1 if improved genotypes are used. 0 if improved genotypes are not used.	0	1
Yield			
Yield	Mg of banana per ha	1.18	95.12
Access to agricultural extension and knowledge			
Support from the Ministry of Agriculture (MAG)	=1 if there is access to MAG support. 0 if there is no access to MAG support.	0	1
Private support	=1 if there is access to private support. 0 if there is no access to private support.	0	1
Years working with banana	Number of years	0	60
Socio-economic characteristics			
Province	=1 for Guayas. 0 for Los Rios	0	1
Size of the production unit	ha per production unit	0.35	2658.90
Hired workers	Contract workers per ha	0	18
Family workers	Family workers per ha	0	8.5
Exportation	=1 if production is for exportation. 0 if production is for local market.	0	1
Agronomic attributes			
Amount of mineral fertilizer	in l or kg per ha	0.00	2500.00
Amount of pesticide	in l or kg per ha	0.00	24.80
Amount of fungicide	in l or kg per ha	0.00	92.00
Amount of organic fertilizer	in l or kg per ha	0.00	5010.00
Waste	Mg per ha	0.00	14.00
Irrigation efficiency	in %	0.50	0.90

2.2. Data Analysis

The data were analyzed using RStudio, version 12.0. A multivariate approach was used to evaluate the relationships between all the variables studied (Pearson's correlation coefficient) using the Factoextra package [35]. Principal component analysis (PCA) was then used to reduce the number of variables into a new set of components using the psych package [36]. Six variables related to banana management practices were chosen for the PCA (use of fertilizer, use of organic inputs, use of fungicides, use of pesticides, use of improved genotypes, and planting density). The Kaiser criterion was utilized to determine the factors, with individual values ranging from 0.55 to 0.84, and an overall value of 0.65. Moreover, Bartlett's test of sphericity was associated with a p-value < 0.001, indicating that the analysis is valid. Evaluating the correlations between the factors, a load > 0.5 or <−0.5 was considered to subsequently name each group (Table 2).

After identifying the factors, cluster, hierarchical, and agglomerative analyses were performed for the management variables using Ward's method to minimize the variance within each cluster with the aid of the cluster package [37]. The square of the Euclidean distance was used to measure the distances. A new spreadsheet was generated, categorizing the data into four distinct groups.

Table 2. Loadings of the four factors resulting from the Principal Component Analysis with their respective eigenvalues and percentage of variance.

Agronomic Management	Factors			
	1	2	3	4
Use of fertilizer	**0.57**	0.04	0.08	−0.23
Use of organic inputs	**−0.38**	0.53	−0.24	0.35
Use of fungicides	**0.42**	0.06	−0.19	**−0.84**
Use of pesticides	**0.59**	0.08	0.04	0.10
Plant density	0.03	**−0.65**	**0.75**	0.11
Use of improved genotypes	−0.08	**−0.68**	**0.58**	−0.32
Eigenvalues	2.34	1.31	1.14	1.03
Variance (%)	39.00	20.04	14.30	11.84
Cumulative variance (%)	39.00	59.07	73.37	85.21

In bold, loads greater than 0.5 or less than −0.5.

The analysis of variance (ANOVA) was carried out using the Agricolae package [38] to test for differences between clusters for all the variables in the different categories: agronomic management, yield, access to agricultural extension and knowledge, socioeconomic characteristics, and agronomic attributes. For the variables with statistical significance (<0.05), Fischer's LSD test was used to differentiate the means between clusters.

The multiple linear regression was performed in order to define a linear relation between the yield of banana and the predictor variables (access to agricultural extension and knowledge, socio-economic characteristics, and agronomic attributes) for each of the clusters previously defined. Cluster 4 was excluded because it had an insufficient number of production units. This analysis was performed using the backward elimination of variables [39]. In the backward selection process, the model starts with all of the predictors (complete model), and, at each stage, variables that contribute the least to the model are iteratively removed. The normality of the residuals was assessed using the Shapiro–Wilk test, with p-values greater than 0.05 indicating a normal distribution and the Breusch–Pagan test was used to verify homoscedasticity. The occurrence of multicollinearity between predictors was evaluated using the Variance Inflation Factor (VIF). If the VIF is greater than 10, then multicollinearity is no longer acceptable [40].

3. Results and Discussion

3.1. General Characteristics

The Pearson correlation analysis provides a comprehensive overview of the current state of banana production in Ecuador (Figure 2). The analysis indicated a significant positive association between the use of fertilizers and fungicides and yield, with yield also showing a strong correlation with export levels ($p < 0.001$). However, it is important to note that high yields are often linked to increased waste, a topic discussed below. In addition, waste is positively associated with the adoption of high-density planting, fungicide use, and irrigation efficiency. Another key finding is that the amount of fungicide used correlates positively with both private and government support, suggesting that fungal diseases such as Sigatoka are significant challenges in banana production [41].

Improved banana genotypes are positively associated with the use of fertilizers, fungicides, and pesticides. However, the amount of fungicide applied was negatively related to these improved genotypes, indicating that newer varieties may be less susceptible to pests. Furthermore, farmers with more years of experience in banana cultivation tend to show a negative correlation with innovation and adoption of improved genotypes. This is consistent with previous research, which reported that introducing new technologies on long-established farms is a difficult task, primarily because of high adoption costs [42]. Finally, support from the Ministry of Agriculture is negatively correlated with exports and irrigation efficiency, suggesting that government assistance primarily benefits small farmers rather than larger producers.

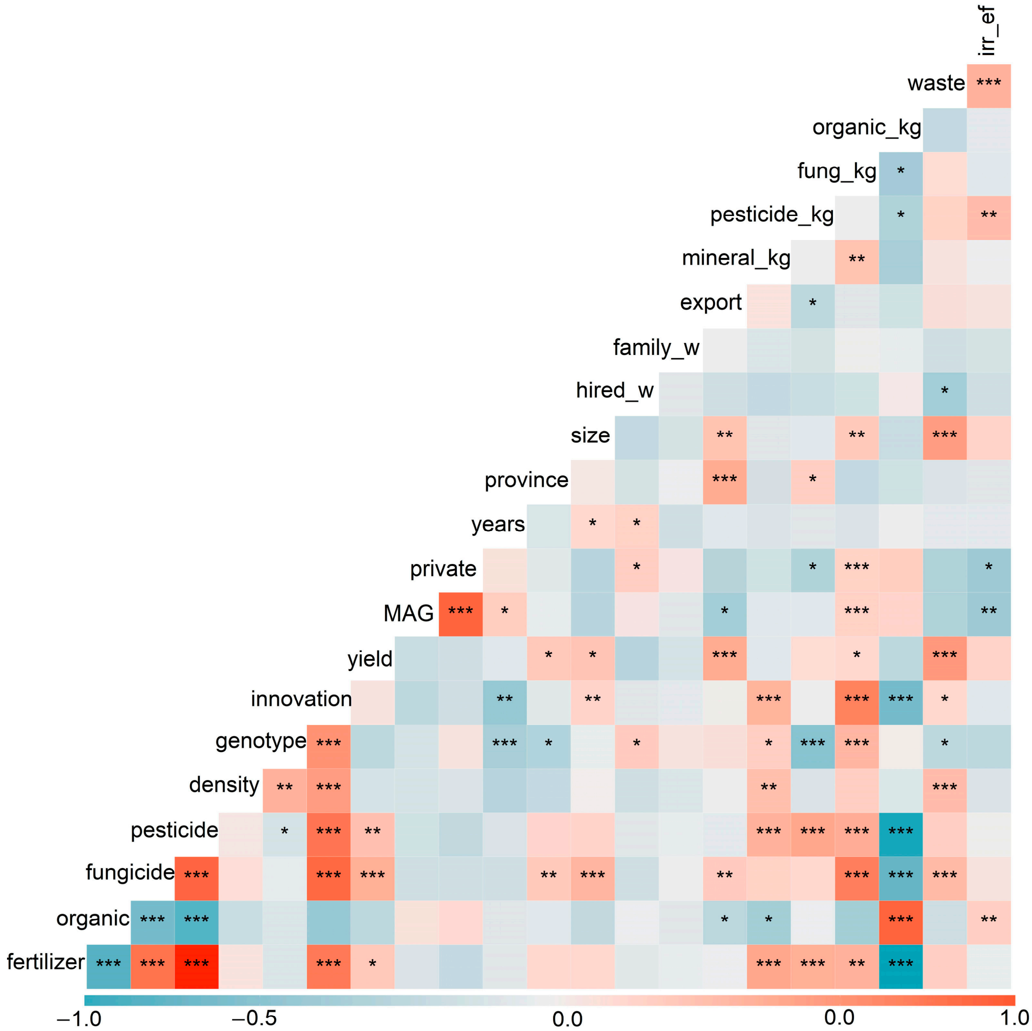

Figure 2. Pearson correlation analysis ($n = 319$) between all variables included in this study (agronomic managements, access to agricultural extension and knowledge, socio-economic characteristics, and agronomic attributes). Significance levels are indicated by * ($p < 0.05$), ** ($p < 0.01$) and *** ($p < 0.001$).

According to Table 3, 95% of the production units commonly use fertilizer, 15% use organic inputs, 72% use fungicides, 93% use pesticides, 9% use high planting density, and 49% use improved genotypes. Mineral fertilizer is applied at a rate of 874 kg ha^{-1} while organic fertilizer is applied at an average of 77 kg ha^{-1}. The amount of fungicide applied is 10.1 kg ha^{-1} while pesticides are used at an average of 6.3 kg ha^{-1}. On average, 3.1 management technologies have been adopted in the six production units analyzed in this study. It is worth noting that the average yield is 49 Mg ha^{-1} and that waste amounts to 1.2 Mg ha^{-1} (losses of 2.4% in relation to yield). Results suggest that the banana crop is managed as an intensive crop with high use of fungicides, pesticides, and fertilizers [43]. On the other hand, the low use of improved genotypes that help reduce the risk of yield penalties due to pests and diseases may be associated with the higher cost of this genetic material [44]. Moreover, the low use of organic inputs may be related with various factors such as a lack of education among producers [45], which, in Latin America, Asia, and Africa are still little explored [46].

Considering the socioeconomic factors, it is important to recognize that 10% of the production units received support from the Ministry of Agriculture, while 31% received support from the private sector. The average years of experience for farmers in the banana sector was 19.6 years, with a range of 0–60 years. The size of the production units varied greatly, from 0.35 to 2670 ha, with an average size of 136 ha. On average, each production unit employed 6.1 hired workers and 1.4 family workers. It is worth noting that 91% of production is intended for export. In general, despite the fact that banana crops are a critical component of Ecuador's economy, insufficient government support has been provided to advance the technology. For example, the country investment in research and development in agriculture is less than 0.4% of its gross domestic product [47], one of the lowest in the region. Therefore, offering aid to farmers can significantly boost their productivity and competitiveness.

Table 3. Characteristics of the four identified clusters, including p-values and the analysis of variance. Means within a row followed by distinct letters are different by the LSD test at 0.05 significance.

Variable	**Average Value**	**Cluster 1 (n = 27)**	**Cluster 2 (n = 92)**	**Cluster 3 (n = 185)**	**Cluster 4 (n = 15)**	**p-Value**
Agronomic managements						
Use of fertilizer	0.95	1.00 a	0.97 a	0.98 a	0.00 b	0.000
Use of organic inputs	0.15	0.00 c	0.40 b	0.00 c	0.73 a	0.000
Use of fungicides	0.72	0.81 b	0.24 c	1.00 a	0.00 d	0.000
Use of pesticides	0.93	1.00 a	0.91 b	1.00 a	0.00 c	0.000
Plant density	0.09	1.00 a	0.01 c	0.01 c	0.07 b	0.001
Use of improved genotypes	0.49	0.74 a	0.47 b	0.45 b	0.67 ab	0.019
Number of managements adopted	3.13	4.56 a	3.03 c	3.45 b	1.47 d	0.000
Yield						
Yield in Mg ha^{-1}	49.03	46.68 a	45.83 b	51.65 a	40.64 b	0.001
Access to agricultural extension and knowledge						
Support from the Ministry of Agriculture (MAG)	0.10	0.11	0.12	0.10	0.07	0.980
Private support	0.31	0.31	0.27	0.32	0.43	0.660
Years working with banana	19.63	16.44	19.62	20.18	18.73	0.563
Socio-economic characteristics						
Province	0.53	0.48 ab	0.48 ab	0.58 a	0.33 b	0.041
Size of the production unit	136.13	160.16 a	88.72 b	161.85 a	66.53 b	0.008
Hired workers	6.07	3.52 b	7.53 a	5.86 ab	4.20 ab	0.039
Family workers	1.42	1.00	1.07	1.69	1.07	0.812
Exportation	0.91	0.93 ab	0.83 b	0.94 a	0.93 ab	0.025
Agronomic attributes						
Amount of mineral fertilizer	874.13	1304.96 a	870.66 b	883.85 b	0.00 c	0.001
Amount of pesticide	6.26	8.71 ab	8.43 a	5.62 b	0.00 c	0.000
Amount of fungicide	10.10	0.81 b	0.24 c	1.00 a	0.00 d	0.000
Amount of organic inputs	77.29	0.00 b	83.79 b	0.00 b	1129.80 a	0.000
Waste	1.22	3.24 a	0.69 c	1.29 b	0.04 c	0.000
Irrigation efficiency	0.84	0.83	0.84	0.83	0.83	0.743

3.2. Cluster and Principal Component Analyses Based on Banana Management

The principal component analysis of the six agronomic management variables resulted in the extraction of four factors, which accounted for 85.2% of the total variance (Table 2). The first factor accounted for the highest percentage of variance with 39.0%. This factor was positively correlated with the use of fertilizers and fungicides. The second factor accounted for 20% of the variance; it was positively correlated with the use of organic inputs and negatively correlated with planting density and the use of improved genotypes, suggesting that these practices are mutually exclusive. The third factor accounted for 14.3% of the variance and was related to planting density and the use of improved genotypes. The fourth factor accounted for 11.8% of the variance and was negatively associated with fungicide use. The correlations of each factor suggest the identification of properties within a particular cluster as mentioned by Priegnitz et al. [48].

The cluster analysis resulted in the formation of four groups. Cluster 2 was separated from the others by the high use of organic inputs and low planting densities and the lower use of improved genotypes (Cluster 2, according to the principal component analysis, is related to factor two). Cluster 3 was separated from the other clusters by the high use of fertilizers and pesticides (Cluster 3, according to principal component analysis, is related to factor one). Cluster 1 was separated from the others by the high density of planting and the use of improved genotypes (Cluster 1, according to principal component analysis, is related to factor three). Cluster 4 was separated from the others by the exclusion of fungicide use (Cluster 4, according to principal component analysis, is related to factor four). The differences between these clusters can be seen more clearly in Figure 3, where the percentages of agronomic management adopted in each cluster are shown in a radial diagram. In this study, it was possible to associate the PCA factors with the groups created from the cluster analysis in a similar way to that reported by Granato et al. [49] in the area of food science. These authors conclude that the use of PCA and cluster analysis simplifies the interpretation of similarity and hidden patterns for groupings.

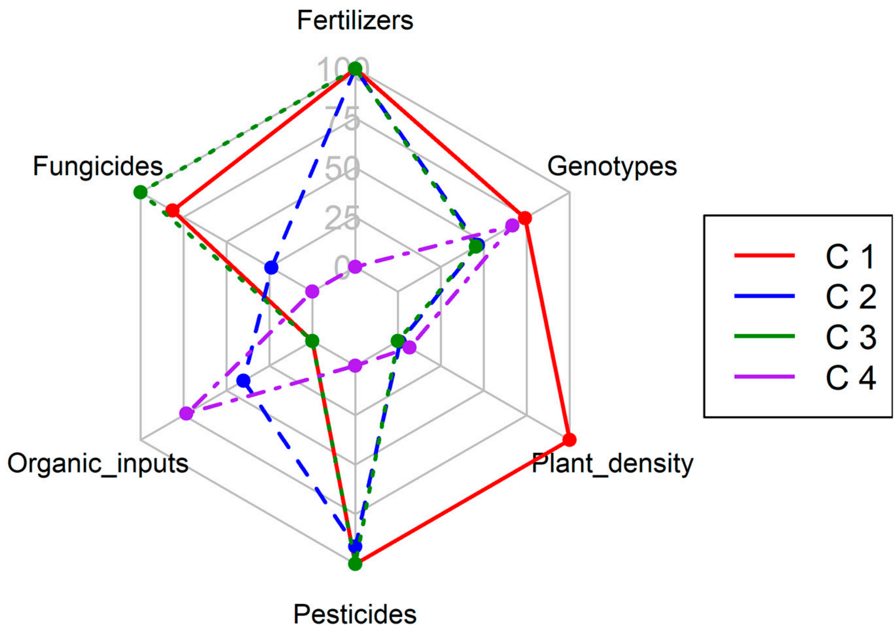

Figure 3. Radial graphic with percentages of agronomic managements adopted in each cluster.

3.3. Classification of Production Units According to Cluster Analysis

Table 3 presents the results for all the variables examined in the four groups created after the cluster analysis. The designation of each group was based on the number of agronomic management practices employed and the types of management used in each cluster. The characterization of each group took into account the variables with statistical significance ($p < 0.05$), while the variables without significance were excluded from the characterization of each group of production units.

Cluster 1: Conventional high-tech farms represented 8.5% of the production units ($n = 27$). Of the farmers in this group, 100% use fertilizer, pesticides, and high planting density, 81% use fertilizer, and 74% use improved genotypes. It is worth noting that the farmers in this group do not use organic inputs. The number of agronomic managements adopted by this group was on average 4.6. The yield per unit area was higher compared to Clusters 1 and 4 and similar to Cluster 3 (46.7 Mg ha^{-1}). Other important characteristics that differentiate this group from the other clusters include the fact that 93% of production is exported and that the farms are large (160 ha). However, this group is responsible for the highest rate of banana waste (3.2 Mg ha^{-1}).

Cluster 2: Balanced conventional farms represented 28.8% of the production units ($n = 92$). Of the farmers in this group, 97% used fertilizer, 40% used organic inputs, 24% used fungicides, 91% used pesticides, and 47% used improved genotypes. However, they did not use high planting density. The average number of agronomic management practices adopted by this group was 3.0. The yield per unit area was lower than those of Clusters 1 and 3 (45.8 Mg ha^{-1}). In addition, the size of the farms and the percentage of bananas exported are smaller when compared to Clusters 1 and 3, 88.7 ha and 83%, respectively.

Cluster 3: Intensive conventional farms account for 58% of the production units (*n* = 185). Of the farmers in this group, 98% used fertilizer, 100% fungicides, 100% pesticides, 1% high planting density, and 45% used improved genotypes. No organic input was used in this group. On average, the number of agronomic management practices adopted by this group was 3.5 on average. The yield per unit area was the highest, along with that of Cluster 1 (51.7 Mg ha^{-1}). Other important characteristics that differentiate this group from the other clusters include the export of 94% of production and the fact that the farms are large, averaging 162 hectares.

Cluster 4: Agroecological farms represented 4.7% of production units (*n* = 15). Of the farmers in this group, 73% used organic inputs, 7% had a high planting density, and 67% had improved genotypes. Fungicides, mineral fertilizers, and pesticides were not used in this group. The average number of agronomic managements adopted by this group was 1.5. The yield per unit area was lower, similar to that of Cluster 2 (40.6 Mg ha^{-1}). The size of the properties is smaller compared to Clusters 1 and 3 (67 ha) and it is noteworthy that in this cluster waste is low (0.04 Mg ha^{-1}).

3.4. Multiple Linear Regression

The multiple linear regression models exhibited adjusted R^2 values ranging from 0.15 to 0.52 (Table 4). Cluster 1 attained the highest adjusted R^2 value of 0.52, indicating a more robust model fit compared to Clusters 2 and 3. The adjusted R^2 took into account the number of predictors and the sample size in order to correct the R^2 in each model. Among the 14 predictor variables originally examined in this study, seven were found to be pertinent for at least one multiple linear regression model.

Table 4. Multiple regression models explaining yield of banana per unit of area.

	Cluster 1	**Cluster 2**	**Cluster 3**
Adjusted R^2	0.52	0.26	0.15
Probability	***	***	**
N	27	92	185
Access to agricultural extension and knowledge			
Support from the Ministry of Agriculture (MAG)	ns	ns	ns
Private support	ns	ns	ns
Years working with banana	ns	ns	ns
Socio-economic characteristics			
Province	ns	(+) ***	ns
Size of the production unit	(−) *	(−) *	ns
Hired workers	ns	ns	ns
Family workers	ns	(+) *	ns
Exportation	ns	ns	(+) ***
Agronomic attributes			
Amount of mineral fertilizer	ns	ns	ns
Amount of pesticide	ns	ns	ns
Amount of fungicide	ns	ns	(+) *
Amount of organic inputs	ns	ns	ns
Waste	(+) ***	(+) ***	(+) ***
Irrigation efficiency	ns	(+) *	ns

+/−: positive/negative estimator. ns: not significant. significance levels: * 0.05; ** 0.01; *** 0.001.

No significant effects were observed across all clusters concerning support from the Ministry of Agriculture (MAG) or private support. This could be because support from the MAG and the private sector was not effectively tailored to the specific needs of banana farmers. Additionally, the number of years working with bananas did not significantly affect yield, which is consistent with the study of Zhang et al. [50], who found that the level of education impacts yield rather than the experience of farmers.

Regarding socioeconomic characteristics, the province is significant only for Cluster 2, indicating that regional factors play a crucial role in differentiating this cluster. This is supported by the fact that, among the three clusters, Cluster 2 adopted fewer management practices (Table 3), suggesting a higher dependence on spatial characteristics, such as climatic and soil variables. Additionally, family workers had a positive effect on Cluster 2, indicating that family labor was more prevalent or effective in this cluster. The size of the production unit has a negative and significant effect on yields in both Clusters 1 and 2, implying that larger production units are associated with lower yields in these clusters. Family exportation is significant only for Cluster 3, suggesting that producers in this cluster are more likely to engage in export activities.

Analyzing agronomic characteristics, the utilization of fungicides exhibited a positive association with Cluster 3, indicating a higher inclination towards using fungicides in this cluster to enhance banana production. This may be because banana cultivation in Ecuador is highly susceptible to transboundary fungal diseases [41], which require the application of large quantities of fungicides. Given this situation, it is worth noting the initiatives taken to introduce genome-editing platforms in Ecuador to generate transgenic-free edited banana plants [51]. Irrigation efficiency was positive for Cluster 2, suggesting that drip irrigation led to higher yields, which is consistent with the study of Yang et al. [52], who demonstrated their positive impacts on grain yield and water use efficiency. Ultimately, waste emerged as a crucial concern across all clusters, exhibiting a positive relationship, indicating that units with higher banana yields per unit of land may encounter challenges during postharvest and marketing process.

4. Conclusions

In Ecuador, banana production units use fertilizers, pesticides, and fungicides to improve yields. Despite the efforts of the Ministry of Agriculture, mainly involving small farmers, this assistance may not effectively target yield improvement. Notably, producers with more years of experience exhibited a negative correlation with the number of innovations adopted and the use of improved genotypes.

Four distinct types of production units were identified: conventional high-tech, conventional balanced, intensive conventional, and agroecological. Conventional high-tech and intensive conventional farms, which represent 66.5% of the studied units, achieve the highest yield and are relatively large, with an average of 93.5% of their production exported.

Each group demonstrates distinct factors influencing yield. For example, conventional balanced units depend more on regional factors, family labor, and irrigation efficiency, whereas intensive conventional farms rely heavily on fungicide application. Consequently, public policies should be tailored to the specific characteristics of each cluster to facilitate effective technology transfers.

A limited number of production units employ organic inputs, which can command higher selling prices. However, economic data for these units are not available in the INEC database. Future studies should investigate the economic viability of each group.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriengineering6030163/s1.

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