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RESEARCH ARTICLE

# Analysis of the Concentration and Specialization of the Sugarcane Production (*Saccharum officinarum* L.) in Colombian Municipalities between 2007 and 2021

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**Abstract:** Sugarcane (*Saccharum officinarum* L.) is a traditional tropical crop that in 2021 represented 58.4% of agricultural production in the Colombia, reaching 42.7 million tons of which 86.2% came from 6 departments. Given that 625 municipalities of a total of 1,121 reported sugarcane production, the objective of this article is to analyze the concentration and specialization of sugarcane production in Colombian municipalities between 2007 –2021. The methodology analyzes three statistical databases applying Gini coefficient, Location Coefficient (LQ),Herfindahl-Hirschman Index (HHI) and Moran index, to identify the Agricultural Clusters (CA) in the Colombian sugarcane sector, that are complemented with bivariate thematic cartography. Additionally, sugarcane, production, LQ and HHI are correlated with Multidimensional Poverty Index (MPI) for 2018.The results reveal that in 2021, the regional Gini was 0.846, and the municipal Gini was 0.932; there were 215 municipalities identified with LQ greater than 1.0, 163 of which were among the 20% of the highest values. Likewise, there were 255 municipalities where sugarcane represented more than 50% of total agricultural production. Additionally, in 2018, MPI showed higher levels in rural areas of the sugarcane municipalities (average 26.3%, maximum 98.9%, minimum 0.0%); there was only inverse correlation with LQ and HHI in municipalities white sugarcane production for sugar, yet in panela and honey the correlation is low and not statistically significant. In conclusion, a significant regional and municipal concentrations of sugarcane production are observed in Valle del Cauca, Cauca, Santander, Cundinamarca, Boyacá y Antioquia (86.2% of total production). These results should be of interest to regional and municipal governments, guilds institutions, and public policymakers in agriculture and rural development, especially, on issues related to climate change, production costs, associative programs and promotion of the agroindustry.

**Keywords:** Sugarcane production; Agricultural clusters; Productive concentration; Productive specialization

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# 1. Introduction

Sugarcane is a plant belonging to the grass family of the genus *Saccharum*, from Southeast Asia and New Guinea, from where it arrived in Spain in the 9th century with the Muslim expansion and subsequently was introduced to America in the 15th century. It arrived in Colombia at the beginning of the 16th century and was first planted in Santa Maria Antigua del Darien (around 1510), later it was taken to Cartagena (1533) and Buenaventura (1540). The commercial sugarcane varieties are hybrids mainly of *Saccharum officinarum*, *Saccharum spontaneum* and *Saccharum robustum*. Sugarcane (*Saccharum officinarum*) is a plant cultivated in tropical and subtropical zones at an average temperature of 25°C, with the capacity to adapt from sea level altitudes up to 2,200 masl [1]. The main climatic factors that affect the crop, yield and quality of sugarcane are temperature, light and humidity[2, 3].

Although the crop is currently used mainly as a raw material for sugar processing and production, sugarcane is also used to produce distilled alcoholic beverages such as rum, charanda, aguardiente and cachaza. Additionally, in tropical countries, panela, piloncillo, chancaca, papelón or rapadura are processed, which is a highly-demanded food in Colombia, Ecuador, Peru, Venezuela, Panama and Mexico [2, 4, 5]. In this respect, Sánchez and Forero[3] argue that Colombia is the second world producer of panela after India, and the first in per capita consumption, which confirms the importance of sugarcane cultivation for the national economy. In addition, Ortiz-Sanchez et al. [1] confirm that panela is the second most important rural agribusiness after coffee in Colombia.

In Colombia, sugarcane is cultivated with the *Saccharum officinarum* species; however, with genetic improvement and plant breeding, there are different varieties that adapt to different biophysical conditions. Likewise, sugarcane production is subdivided into sugarcane for sugar production, panela production and honey production, with the department of Valle del Cauca being the main producer of sugarcane concentrated in large tracts of land around industrial complexes known as mills.

For its part, panela cane is produced in 28 departments, and sugarcane fields are owned by more than 350,000 families in productive systems associated with small and medium-sized agricultural production [5].

On the other hand, world sugarcane production in 2021 registered 1,966 million tons (approx.) in a harvested area of 27.4 million hectares (approx.), where the main producers were Brazil (36.4%), India (20.6%), China (5.5%), Pakistan (4.5%), Thailand (3.4%), Mexico (2.8%), Colombia (2.1%) and Indonesia (1.6%)[6]. In Colombia, sugarcane production was 42.7 million tons with a percentage variation of 0.6% with respect to the previous year, of which 86.2% came from 6 departments: Valle del Cauca (57.9%), Cauca (12.1%), Santander (4.8%), Cundinamarca (4.1%), Boyacá (3.7%) and Antioquia (3.6%). Among the 1,121 municipalities in the country, 625 reported production, the most representative being Palmira (11.2%), Candelaria (6.2%), El Cerrito (4.8%), Guacarí (3.9%) and Florida (3.0%)[7]. The data reflect a regional and municipal concentration; therefore, it is pertinent to study the agglomeration and specialization of sugarcane production in Colombia.

With respect, for concentration measurements, the Gini coefficient and the Lorenz curve have traditionally been implemented[8], while for the measurement of productive specialization, the location coefficient (LQ) is used by Schouten and Heijman[9, 10]. According to Castro and Fuentes [8], there is valuable evidence on economic concentration and specialization in industrial activities, however, there is less evidence available that can address the issue of agricultural activities. This work provides important information on the concentration and specialization of sugarcane production in the municipalities of Colombia.

The conceptual framework of this work supports the idea of *agricultural clusters* proposed by FAO[11], consequently, agriculture in the 21st century must achieve higher levels of productivity, for this reason, *agro-based clusters* (ABCs) are a sectoral organization tool for government institutions and public policies [11]. The ABCs are "geographic concentration of interconnected producers, agribusinesses and institutions that participate in the same agricultural or agro-industrial subsector and create value networks to address common challenges and seek joint opportunities"[12]. Additionally, Otsuka and Ali[13] classify ABCs between *agricultural clusters* (AC) that market fresh produce without strict grading and processing, and *agro-industrial clusters* (AIC) that include value-added and transformation processes. The main challenge for developing countries is to dynamize ABCs and transform their ACs into AICs [13]. The ABCs contribute to the articulation of the actors in the *value chain*, promote innovation, competitiveness and relations with support organizations [11]. ABCs analysis is a necessity for the contemporary agricultural economy [14]. This work provides relevant information on the AC of sugarcane at the municipal level.

Considering that in 2021, 55.8% of the Colombian municipalities registered sugarcane production, and that 90.1% of national sugarcane production was concentrated in 100 municipalities (8.9% of the total), three research questions arise: 1) Which are the municipalities with the highest level of specialization in sugarcane production? 2) Are there agricultural clusters in Colombian sugarcane production? 3) Does specialization in sugarcane production have any association with the rural multidimensional poverty? Our hypothesis suggests that there is an inverse relationship between the concentration and specialization of sugarcane production measured by the location coefficient (LQ) and the Herfindahl-Hirschman Index (HHI), and the incidence of multidimensional poverty in the *populated rural centres and dispersed rural areas* (PRCDRA) of sugarcane production municipalities, indicating that municipalities with a higher level of specialization in sugarcane production have lower rates of multidimensional poverty in PRCDRA. In this sense, the objective of this article is to analyze the concentration and specialization of sugarcane production in Colombian municipalities between 2007–2021, through the application of the Gini coefficient, the location coefficient (LQ), the Herfindahl-Hirschman Index (HHI) and autocorrelation by Moran's index, to identify the agricultural clusters (CA) of Colombian sugarcane production. LQ measures specialization through the volume of annual municipal sugarcane production in tons, while HHI measures specialization according to the annual amount of land cultivated with sugarcane production by municipality. The measurements were carried out mainly for the years 2007 (start), 2014 (medium) and 2021 (final). Additionally, the document provides thematic cartography at the municipal scale to visualize the spatial distribution of production, agronomic yield (t/ha), LQ, HHI, Moran index and the Multidimensional Poverty Index (MPI) in PRCDRA (the latter only for 2018).

Finally, the results of this work aim to make a contribution to the study of the Colombian agrarian and regional economy, where sugarcane is a representative icon of the culture and agricultural vocation of the country, especially with panela. To the best of our knowledge, this article is a first look at the Gini coefficient, LQ, HHI and Multidimensional Poverty Index (MPI) in sugarcane production areas in Colombia, and additionally, using bivariate cartography. The remainder of the paper is organized as follows: Section Two describes the databases used, variables and analysis techniques implemented; Section Three presents the results; Section Four is discussion; Section Five is conclusions.

## 2. Materials and Methods

### 2.1 Description of the Study Area

According to *National Administrative Department of Statistics* (DANE), Colombia has 32 Departments (or regions) and 1,121 municipalities (1,102 municipalities, San Andres Island and 18 non-municipalized areas-ANM) [15]. In 2021, 625 municipalities (55.7% of the total) registered sugarcane production. The official layers (shp) of the Geoportal of the Instituto Geográfico Agustín Codazzi (IGAC, 2022) are used to prepare the thematic cartography [16].

### 2.2 Data and Variables

Three statistical databases were used:

1 Report of the Municipal Agricultural Evaluations (EVA) [Agricultural Base EVA from 2019 to 2021—Publication date 22042022], from the Agriculture Rural Planning Unit and the Ministry of Agriculture and Rural Development [7].

2 Report of the Municipal Agricultural Evaluations (EVA) [Agricultural Base EVA from 2007 to 2018 (P)_12_02_2020], from the Agricultural Rural Planning Unit and the Ministry of Agriculture and Rural Development [17]. These first two bases contain

statistics for the 1,121 Colombian municipalities, related to *area planted* (measured in hectares), *area harvested* and *production* (measured in tons), for a diverse range of 150 crops. These crops are classified into eight typologies namely: cereals, fruits, vegetables, legumes, oilseeds, roots and tubers, traditional tropical crops, and crops for condiments and medicinal and aromatic beverages.

3 Database of the "Municipal multidimensional poverty measure from census source 2018", from the National Administrative Department of Statistics [18]. This database contains information from the *Multidimensional Poverty Index* (MPI) for the 1,121 municipalities of the Colombia, disaggregated into three categories: *total poverty by municipality*, in *municipal urban areas* and in *populated rural centres and dispersed rural areas* (PRC-DRA). The IPM data correspond to the information recorded in the *National Population and Housing Census*-2018.

## 2.3 Data Analysis Techniques

The statistical information is analyzed in five stages:

1 *Sugarcane production in Colombia between 2007 and 2021*: a description of the data is made at the department and municipality level, and additionally, a brief description is made according to the destination of sugarcane production (sugar, panela and honey).

2 *Concentration of sugarcane production*: the *Gini coefficient* is applied at the departmental and municipal levels for the years 2007, 2014 and 2021. The *Gini coefficient* quantifies the concentration of a variable taking values between 0 and 1, where 1 represents concentration or absolute inequality and 0 represents equal distribution. Complementarily, the *Lorenz curve* is added, which is a graphical way of showing the distribution of the variable [19]. The concentration occurs with respect to the *agglomeration of volume production per municipal unit*.

The measurements were made for the years 2007 (start), 2014 (medium) and 2021 (final). It is necessary to mention that agricultural production is strongly determined by environmental and geographic conditions, and therefore, the Gini identifies the concentration of sugarcane production but does not take into account environmental and geographic factors.

3 *Specialization of sugarcane production in municipalities*: the *Location Quotient* (LQ) is applied at the municipal level for the year 2021. LQ quantifies the density of a variable or economic activity in a region with respect to the national total, revealing the productive activities with comparative advantage [9, 20]. Specifically, LQ is a comparative relationship between a locality and a larger reference region with respect to a specific variable, being the most commonly used methodology to identify clusters [20]. LQ can take three values (greater than, less than or equal to 1), where 1.0 indicates that the participation of the variable in regional production is equal to the contribution of that variable to national production; while LQ greater than 1.0 indicates a high level of relative specialization of the region in the variable under study with respect to national production, and vice versa [21]. The following equation is used to measure LQ:

$$LQ = \frac{E_i^j / E_i}{E^j / E} \tag{1}$$

where $E_i^j$ is the sugarcane production (*i*) in municipality *j*; $E_i$ is the sugarcane production (*i*) in Colombia; $E^j$ is the total agricultural production in municipality *j*; $E$ corresponds to the total agricultural production in Colombia [9, 21].

In addition, this article analyzes agricultural productive specialization through the application of the Herfindahl-Hirschman Index (HHI):

$$\text{HHI}_j = \sum_{h=1}^{H} (\frac{L_{jh}}{L_j})^2 = \sum_{:}^{\cdot} (\frac{L_{jh1}}{L_j})^2 + (\frac{L_{jh2}}{L_j})^2 + (\frac{L_{jh3}}{L_j})^2 + ... + (\frac{L_{jH}}{L_j})^2 \tag{2}$$

where $L_{jh}$ is the amount of cultivated land (planted area) dedicated to *crop h* in municipality *j*, $L_j$ is the total amount of cultivated land (planted area) in municipality *j*, and *H* is the total number of crops present in the municipality *j*. Note that if all the land in a municipality is dedicated to a single crop, then the specialization index $HHI_j$ is equal to unity ($HHI_j$ = 1), therefore, the greater the number of crops present in a municipality, the lower is the value of $HHI_j$ [22]. Specialization occurs with respect to the sum of the squares of the percentage participation quotas of the amount of land (ha) dedicated to each of the crops present in the municipality. This study focused attention exclusively on sugarcane cultivation, therefore, specialization should be understood as the preference of farmers in municipality *j* to have the largest amount of available land cultivated with sugarcane, which is a perennial crop. This preference could result from the use of comparative advantages type geographical (height, temperature, precipitation and soil), as well as the final destination of the production (sugar, panela or honey). The measurements were made for the years 2018 and 2021.

4 *Spatial autocorrelation (Moran's I)*: this is a geostatistical analysis tool that measures the autocorrelation of spatial units based on the locations and values of entities simultaneously, assessing whether the variable is clustered, dispersed or random [23]. The essay starts from the *null hypothesis* (Ho) which states that the values of the polygons on the map are randomly distributed. When performing the statistical analysis, there are two parameters (*p, z*), where p represents a probability and whenever the value is small it allows us to reject the Ho. On the other hand, the *z* parameter represents the standard deviations and usually when it is very small (close to zero), it indicates that there is not enough statistical evidence to reject the Ho; for this reason, *z* will not always take very high values that can be positive or negative when the value of *p* is very small [24].
The analysis of the Moran index for spatial autocorrelation allows us to know the spatial distribution of the values of the analyzed variable. This implies that if the values tend to be spatially clustered (high values near high values), the Moran index will be positive, and on the contrary, if the values are dispersed (high values near low values), the index will be negative. Whenever the value of *p* indicates the rejection of Ho, and the *z*-scoreis significant, the Moran index greater than zero will indicate a tendency towards *agglomeration*, and conversely, if the index is less than zero then there is a tendency towards *dispersion* [24].

5 *Sugarcane production and multidimensional poverty*: using the database DANE [18], the information was selected corresponding to the *populated rural centres and dispersed rural areas* (PRCDRA) of the sugarcane production municipalities. The data were separated according to the final destination of sugarcane production (sugar, panela and honey). Schematize the variables in bivariate thematic mapping and obtain a Spearman correlation matrix. It was expected that the municipalities with the highest sugarcane production will have low multidimensional poverty rates. The availability of data allows this measurement to be made only for 2018.

# 3. Results

## 3.1 Sugarcane Production (*Saccharum officinarum* L.) in Colombia between 2007 and 2021

In 2021, national production was 42.7 million tons (t), planted area of 521,234.3 ha, harvested area of 479,805.2 ha and average yield of 89.1 t/ha. 86.2% of the production came from 6 departments: Valle del Cauca (57.9%), Cauca (12.1%), Santander (4.8%), Cundinamarca (4.1%), Boyacá (3.7%) and Antioquia (3.6%) (see Figure 1 and Table 1). In contrast, in 2007 production was 22.4 million tons, planted area of 443,457.8 ha, harvested area of 390,194.5 ha and average yield of 57.5 t/ha. During 2007 and 2021, production had a variation of 90.6%, the planted area of 17.5% and the harvested area of 23.0% [7, 17]. Table 2 shows the contrast of percentage changes in sugarcane production between 2007-2021, grouped into four categories: extraordinary increase, outstanding increase, moderate increase and reduction. For his part, Figure 2a,b spatializes the production and agronomic yields (t/ha) of the sugarcane in the municipalities of Colombia for the years 2007 and 2021. The bivariate thematic cartography allows us to identify the municipalities with the highest production and highest yield, as well as the agglomeration in each of the years observed.

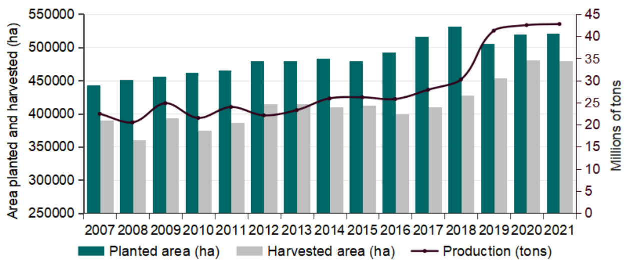
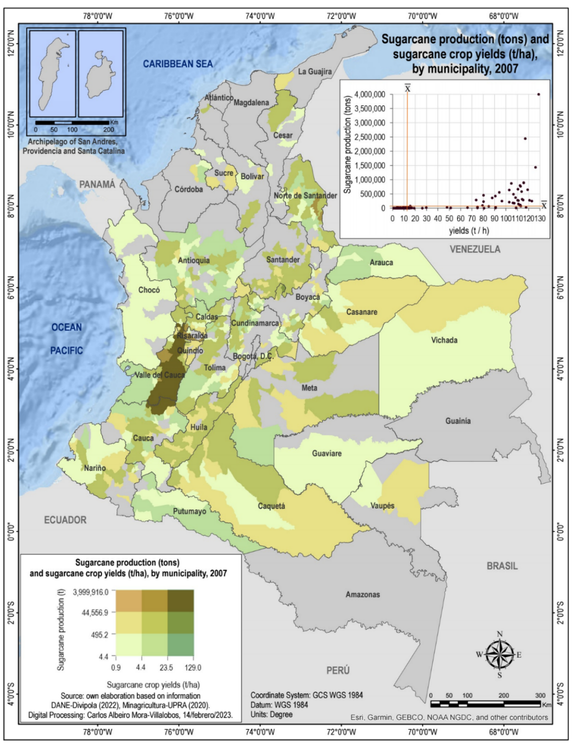



**Figure 1.** Planted area (ha), harvested area (ha) and sugarcane production (t) in Colombia, 2007–2021.

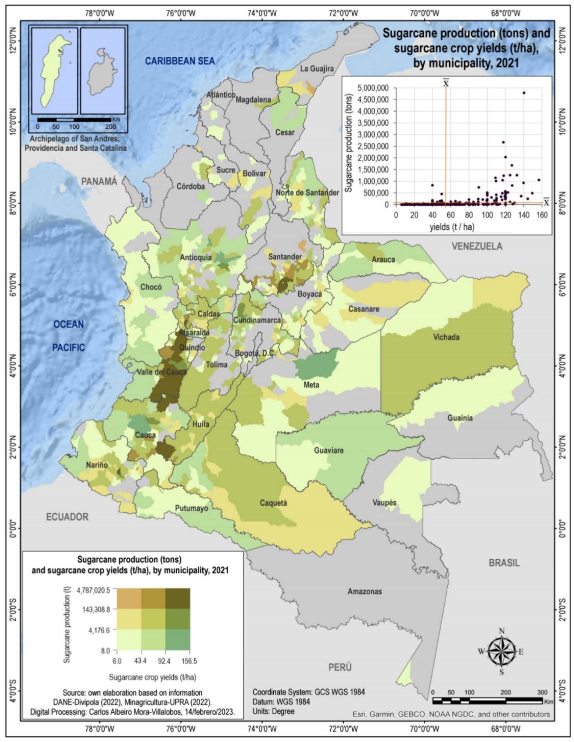
Source: Own elaboration based on data [7, 17].

On the other hand, sugarcane production in Colombia is mainly destined for three agro-industrial processes: production of sugar, panela and honey (see Table 3). Using the database Minagricultura-UPRA [7], the essay takes only the sugarcane production municipalities in 2021, finding that in that year Colombia produced 42.7 million tons of sugarcane, of which, 30.1 million tons were for sugarproduction (70.6%) distributed in




(**a**) Sugarcane production (tons) and yield (t/ha) by municipality, 2007

**Figure 2.** *Cont.*




(**b**) Sugarcane production (tons) and yield (t/ha) by municipality, 2021

**Figure 2.** Sugarcane production (tons) and yield (t/ha) by municipality, 2007 and 2021.

Source: Own elaboration based on data [7, 15].

Note: Intervals use Geometrical Interval methodology, ArcGIS version 10.7.

52 municipalities; 12.4 million tons were for panela production (29.0%) distributed in 558 municipalities; and 181,385 tons were for honey production (0.4%) distributed in 57 municipalities. During 2007 and 2021, cane production destined to produce sugar had a variation of 42.7%, panela production had a growth of 875.3% and honey production grew by 669.3%.

## *Sugarcane Production for Sugar Production, 2021*

It represented 70.6% of total sugarcane production with 30.1 million tons and 54.6% of the total planted area (284,418.7 ha). At the regional level, 8 departments registered production with an average yield of 83.1 t/ha. The departments of Valle del Cauca, Cauca and Meta concentrated 98.0% of the production with yields of 123.7 t/ha, 109.0 t/ha and 40.0 t/ha respectively. At the municipal level, there were 52 producing municipalities and 90.5% of production was grouped in 25 municipalities, the most important being Palmira (15.8%), Candelaria (8.6%), El Cerrito (6.7%), Guacarí (5.6%),

**Table 1.** Sugarcane production (t) (*Saccharum officinarum* L.) by department: 2007, 2014 and 2021.

| | Sugarcane Production (tons) | | | | | |
|---|---|---|---|---|---|---|
| | 2007 | | 2014 | | 2021 | |
| **Department** | **ton** | **%** | **ton** | **%** | **ton** | **%** |
| Valle del Cauca | 17,092,998.0 | 76.2% | 19,649,265.1 | 75.8% | 24,774,517.6 | 57.9% |
| Cauca | 3,562,123.7 | 15.9% | 4,105,205.8 | 15.8% | 5,173,344.0 | 12.1% |
| Santander | 244,655.5 | 1.1% | 186,951.0 | 0.7% | 2,073,657.2 | 4.8% |
| Cundinamarca | 185,438.6 | 0.8% | 178,588.0 | 0.7% | 1,752,942.3 | 4.1% |
| Boyacá | 216,127.6 | 1.0% | 179,646.5 | 0.7% | 1,574,963.7 | 3.7% |
| Antioquia | 158,235.5 | 0.7% | 158,785.8 | 0.6% | 1,518,442.7 | 3.6% |
| Nariño | 80,805.8 | 0.4% | 109,410.4 | 0.4% | 1,018,200.1 | 2.4% |
| Huila | 56,348.0 | 0.3% | 45,239.0 | 0.2% | 939,157.6 | 2.2% |
| Meta | 14,694.6 | 0.1% | 406,130.5 | 1.6% | 887,425.0 | 2.1% |
| Caldas | 295,814.2 | 1.3% | 375,651.8 | 1.4% | 768,698.9 | 1.8% |
| Tolima | 74,544.0 | 0.3% | 68,713.5 | 0.3% | 720,794.2 | 1.7% |
| Risaralda | 312,027.6 | 1.4% | 307,877.1 | 1.2% | 415,065.0 | 1.0% |
| Norte de Santander | 97,584.7 | 0.4% | 62,431.4 | 0.2% | 379,300.1 | 0.9% |
| Caquetá | 9,314.0 | 0.04% | 16,230.3 | 0.1% | 214,748.1 | 0.5% |
| Cesar | 12,201.0 | 0.1% | 20,071.0 | 0.1% | 212,882.8 | 0.5% |
| Bolívar | 5,942.5 | 0.03% | 10,754.0 | 0.04% | 64,457.6 | 0.2% |
| Chocó | 2,710.3 | 0.01% | 4,227.0 | 0.02% | 63,976.2 | 0.1% |
| Putumayo | 4,283.0 | 0.02% | 10,598.0 | 0.04% | 38,164.2 | 0.1% |
| Córdoba | 1,055.0 | 0.005% | 1,175.0 | 0.005% | 33,522.1 | 0.1% |
| Guaviare | 547.8 | 0.002% | 2,220.0 | 0.01% | 33,187.2 | 0.1% |
| Arauca | 4,761.0 | 0.02% | 890.8 | 0.003% | 29,500.0 | 0.1% |
| Magdalena | - | - | - | - | 20,000.0 | 0.05% |
| Quindío | 2,619.6 | 0.01% | 31,622.5 | 0.1% | 19,660.1 | 0.05% |
| Casanare | 5,161.8 | 0.02% | 3,158.2 | 0.01% | 14,981.6 | 0.04% |
| Vichada | 467.0 | 0.002% | 532.6 | 0.002% | 10,329.0 | 0.02% |
| Sucre | 1,054.0 | 0.005% | 1,316.0 | 0.01% | 9,995.4 | 0.02% |
| La Guajira | 352.0 | 0.002% | 462.0 | 0.002% | 5,620.0 | 0.01% |
| Vaupés | 16.0 | 0.0001% | 66.5 | 0.0003% | 599.2 | 0.001% |
| Amazonas | - | - | 6.0 | 0.00002% | 120.0 | 0.0003% |
| Guainía | - | - | 18.0 | 0.0001% | 106.4 | 0.0002% |
| San Andrés Prov.Sta.Cat. | - | - | - | - | 8.0 | 0.00002% |
| | **22,441,882.7** | - | **25,937,243.7** | - | **42,768,366.2** | - |

Source: Own elaboration based on data [7, 17].

Florida (4.2%), Bugalagrande (4.1%), Zarzal (4.1%) and Pradera (3.9%), all in Valle del Cauca [7] (see Figure 3a).

### *Sugarcane Production for Panela Production, 2021*

It represented 29.0% of total sugarcane production with 12.4 million tons and 44.3% of the total planted area (230,682.7 ha). At the regional level, 28 departments registered production with an average yield of 49.7 t/ha. 83.8% of production is grouped in 8 departments. The largest producers are Santander, Cundinamarca, Antioquia and Boyacá with yields of 92.2 t/ha, 47.4 t/ha, 42.3 t/ha and 98.6 t/ha, respectively. At the municipal level, there were 558 producing municipalities and 90.0% of production was grouped in 181 municipalities, the most important being Caparrapí (3.7%) in Cundinamarca; San José de Pare (3.6%), Chitaraque (2.3%) and Santana (1.9%) in Boyacá; Suaita (3.5%), San Benito (1.9%) and Güepsa (1.9%) in Santander; and Isnos (3.2%) in Huila [7] (see Figure 3b).

### *Sugarcane Production for Honey Production, 2021*

It represented 0.4% of total sugarcane production with 181,385.1 tons and 1.2% of the total planted area (6,133.5 ha). At the regional level, 10 departments regis-

**Table 2.** Percentage variation of sugarcane production (t) (*Saccharum officinarum* L.) by department during 2007–2021.

| **Sugarcane production (tons), percentage variation between 2007 and 2021, by departments** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Extraordinary increase** | | **Outstanding increase** | | **Moderate increase** | | **Reduction**** | |
| Guaviare* | 5958.3% | Bolívar | 984.7% | Cauca | 45.23% | - | - |
| Meta* | 5939.1% | Tolima | 866.9% | Valle del Cauca | 44.94% | | |
| Vaupés* | 3645.0% | Antioquia | 859.6% | Risaralda | 33.02% | | |
| Córdoba* | 3077.5% | Sucre | 848.3% | | | | |
| Chocó* | 2260.5% | Cundinamarca | 845.3% | | | | |
| Caquetá* | 2205.6% | Putumayo | 791.1% | | | | |
| Vichada* | 2111.8% | Santander | 747.6% | | | | |
| Cesar* | 1644.8% | Quindío | 650.5% | | | | |
| Huila* | 1566.7% | Boyacá | 628.7% | | | | |
| La Guajira* | 1496.6% | Arauca | 519.6% | | | | |
| Nariño* | 1160.1% | Norte de Santander | 288.7% | | | | |
| | | Casanare | 190.2% | | | | |
| | | Caldas | 159.9% | | | | |

Source: Own elaboration based on data [7, 17].
Note: The table does not relate the departments of Magdalena, Amazonas, Guainía, and San Andrés and Providencia because in 2007 they did not report sugarcane production.
* In the particular case of Guaviare, an increase is observed related only to the production of panela cane. Regarding Meta, 93.6% of production corresponds to sugar cane and the remaining 6.4% to panela cane. Likewise, Chocó has production of honey cane (17.3%) and panela cane (82.7%). For their part, the departments of Vaupés, Córdoba, Caquetá, Vichada, Cesar, Huila, La Guajira, Nariño, Bolívar and Tolima show production only in panela cane.
** None department recorded a reduction in the volume of sugarcane production.

**Table 3.** Sugarcane production according to production destination, 2007, 2014, 2021.

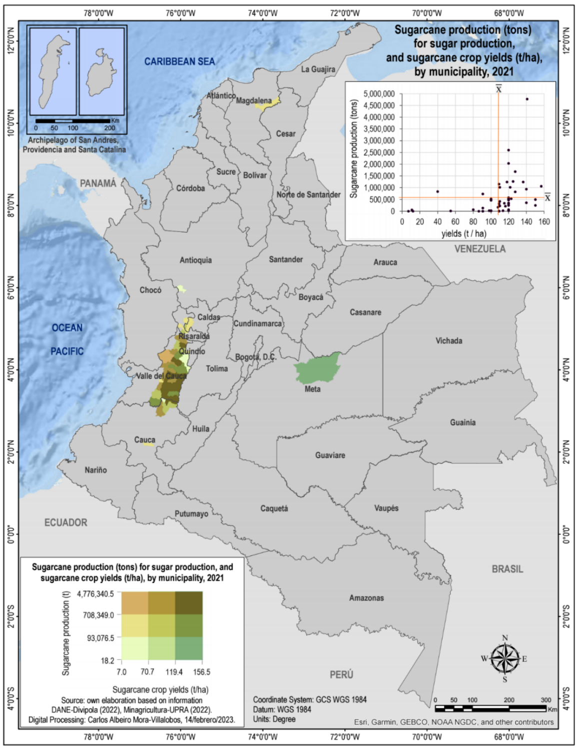
| **Destination of sugarcane** | **Year** | **Planted area (ha)** | **Harvested area (ha)** | **Production (t)** |
|---|---|---|---|---|
| Sugar production | 2021 | 284,418.7 | 263,738.3 | 30,173,224.8 |
| | 2014 | 237,945.4 | 202,192.0 | 24,696,493.9 |
| | 2007 | 203,594.0 | 185,474.0 | 21,145,448.2 |
| Panela production | 2021 | 230,682.1 | 210,533.4 | 12,413,756.4 |
| | 2014 | 240,127.7 | 203,839.5 | 1,226,464.8 |
| | 2007 | 232,839.5 | 198,651.5 | 1,272,855.1 |
| Honey production | 2021 | 6,133.5 | 5,533.5 | 181,385.1 |
| | 2014 | 4,978.2 | 4,057.2 | 14,285.0 |
| | 2007 | 7,024.3 | 6,069.0 | 23,579.4 |

Source: Own elaboration based on data [7, 17].

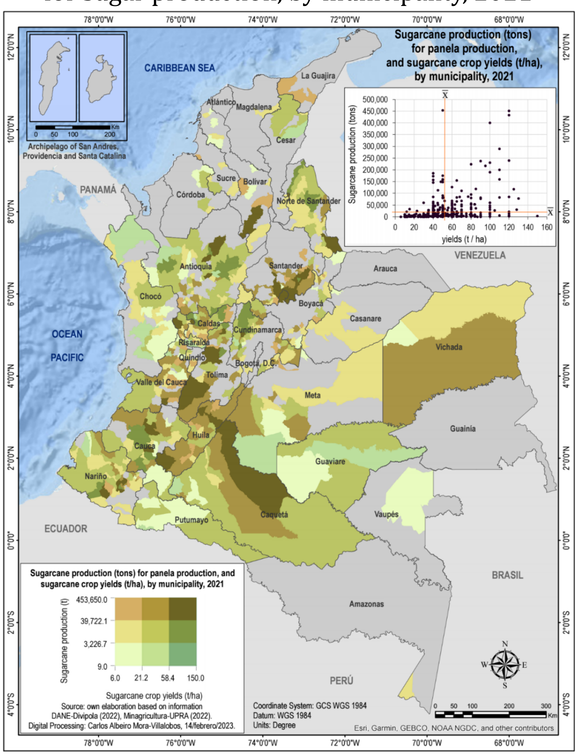
tered production with an average yield of 28.5 t/ha. The departments of Boyacá, Cauca, and Arauca concentrated 82.9% of the production with yields of 37.9 t/ha, 17.0 t/ha and 16.3 t/ha respectively. At the municipal level, there were 57 producing municipalities and 90.3% of production was grouped in 29 municipalities, the most important being López de Micay (11.2%) and Timbiquí (5.8%) in Cauca; Maripí (7.7%), Moniquirá (5.6%), Miraflores (5.4%) and Santa Sofía (4.6%) in Boyacá; and Arauca (4.9%) and Arauquita (5.0%) in the department of Arauca [7] (see Figure 3c).

### 3.2 Concentration of Sugarcane Production, 2007, 2014, 2021

Figure 4 shows a high concentration of sugarcane production at departmental level in terms of Gini index which yielded 0.932 in 2007, 0.929 in 2014, and 0.846 in 2021. For the last year studied, 15.6% of Colombian departments are responsible for 82.7% of sugarcane production. At municipal level, Gini index showed higher values than departmental level with a value of 0.973 in 2007, 0.972 in 2014 and 0.932 in 2021, but with a decrease of 4.1% between 2007 and 2021. In general terms, 6.7% of Colombian municipalities are responsible for 86.4% of national sugarcane in 2021.

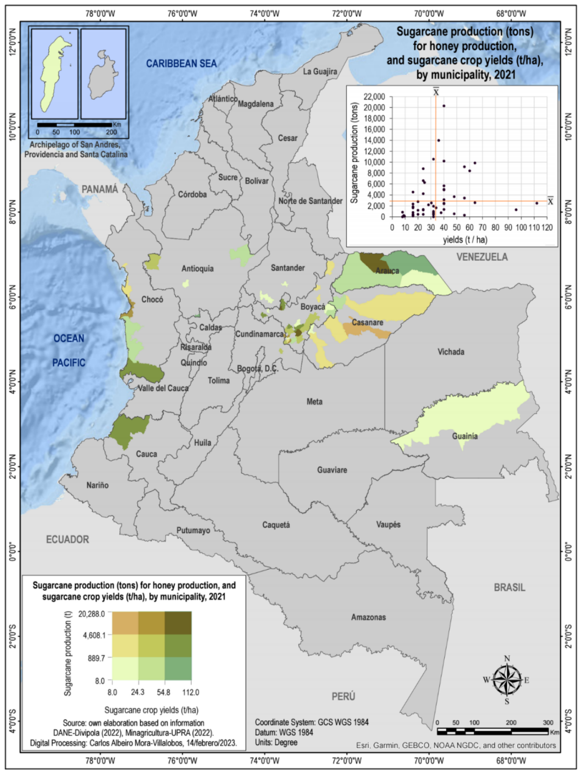



(**a**) Sugarcane production (tons) and yield (t/ha), for sugar production, by municipality, 2021




(**b**) Sugarcane production (tons) and yield (t/ha), for panela production, by municipality, 2021

**Figure 3.** *Cont.*



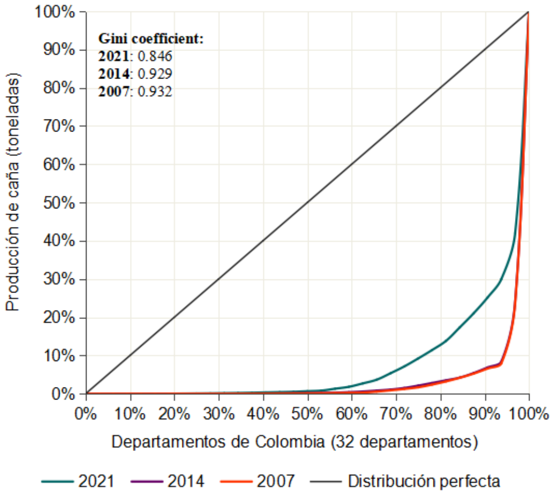

(**c**) Sugarcane production (tons) and yield (t/ha), for honey production, by municipality, 2021

**Figure 3.** Sugarcane production (tons) and yield (t/ha), according to production destination, by municipality, 2021.

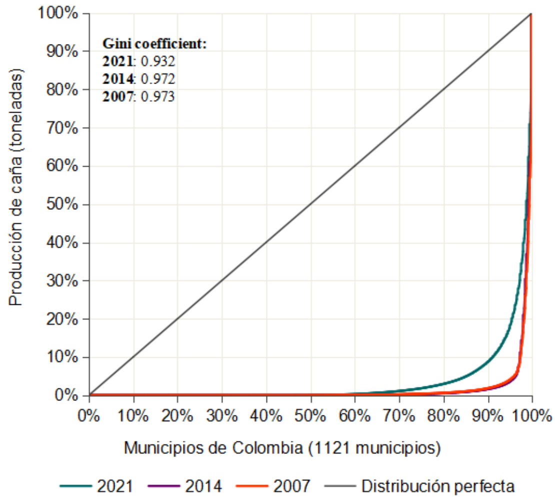
Source: Own elaboration based on data [7, 15].

Note: Intervals use Geometrical Interval methodology, ArcGIS version 10.7.

On the other hand, location coefficient (LQ) shows that in 2021, 34.4% of the municipalities (n = 215) had LQ greater than 1.0 and only one municipality (0.2%) had LQ equal to 1.0. The rest 409 municipalities that represent 65.4% had values lower than 0.99 (see Figure 5). The LQ values in the 215 municipalities with significant values range between 1.009 and 1.711, and it is possible to identify that 80.0% of the frequencies fluctuate between 1.009 and 1.652, the remaining 20%, corresponds to 43 municipalities with the highest values (between 1.654 and 1.711). The five municipalities with the highest LQ values were Útica in Cundinamarca con 1.711; Candelaria and Zarzal in Valle del Cauca (1.710 and 1.707 respectively), and Padilla and Villa Rica in Cauca (1.709 and 1.707 respectively). Comparatively, the 5 municipalities with the highest sugarcane production in 2021 reached the following LQ values: Palmira (1.706), Candelaria (1.710), El Cerrito, (1.703), Guacarí (1.699) Florida (1.680).




(**a**) Lorenz Curve for sugarcane production, by department: 2007, 2014 and 2021




(**b**) Lorenz Curve for sugarcane production, by municipality: 2007, 2014 and 2021

**Figure 4.** Lorenz Curve for sugarcane production, by department (**a**) and by municipality (**b**): 2007, 2014 and 2021.

Source: Own elaboration based on data [7, 17].

## 3.3 Herfindahl-Hirschman Index (HHI), 2021

This section focused attention on sugarcane crop (sowing), therefore, specialization should be understood as the preference of farmers in a certain municipality to sowing sugarcane. Among the 628 sugarcane producing municipalities registered in 2021, an average HHI index for sugarcane crop of 0.071 is observed with a maximum value of 0.983 and a minimum of 0.00000001.To make a classification by quintile, the essay classifies five categories of specialization: very-high (greater than 0.801), high (between 0.601 and 0.80), medium (between 0.401 and 0.60), low (between 0.201 and 0.40) and very-low (between 0.001 and 0.20). It found 12 municipalities (1.9%) with very-high specialization; 16 municipalities (2.5%) with high specialization; 14 municipalities (2.2%) with medium specialization; 23 municipalities (3.7%) with low specialization; and 564 municipalities (89.7%) with very-low specialization. The five municipalities with the highest level of specialization in sugarcane cultivation were: Candelaria in Valle del Cauca (0.983), Útica in Cundinamarca (0.964), Zarzal in Valle del Cauca (0.934), Puerto Tejada (0.930) and Padilla (0.923) in the department of Cauca. Thematic cartography allows the identification of municipalities with very-high and high specialization that are located in the departments of Valle del Cauca, Cauca, Cundinamarca, Boyacá, Santander and Antioquia.

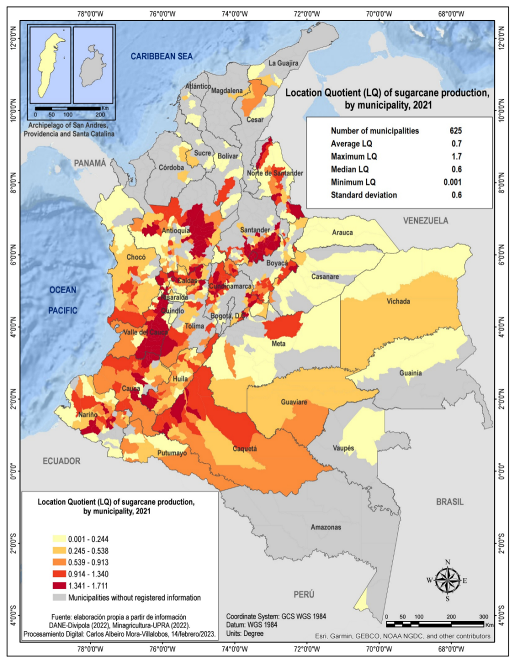



**Figure 5.** Location Coefficient (LQ) of sugarcane production, by municipality, 2021.

Source: Own elaboration based on data [7, 15].

Note: Intervals use Natural Breaks (Jenks) methodology, ArcGIS version 10.7.

Figure 6 shows HHI data for 2021, in which two quantitative variables intersect: *HHImunicipality_2021* indicates that the municipality may or may not have a level of specialization in agricultural production but may not identify the specialization crop. *HHIsugarcane_2021* indicates whether or not the municipality has specialization in sugarcane cultivation. Find an intercept of the two variables (HHImunicipality_2021 and HHI*sugarcane*_2021), and then it is identified that it is a municipality that has revealed specialization in sugarcane crop.

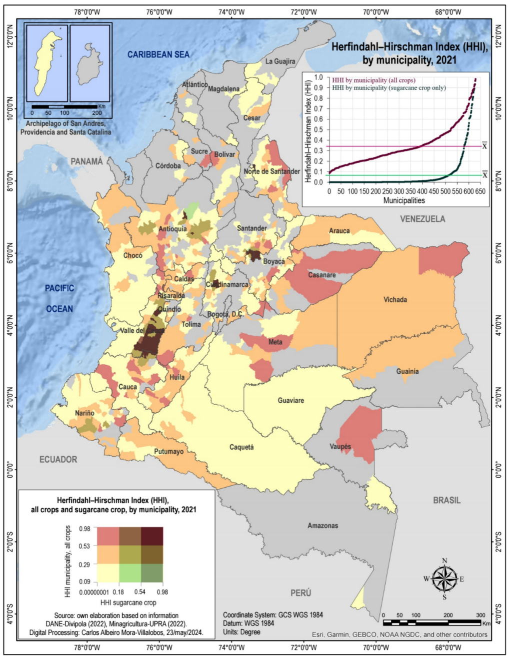



**Figure 6.** Herfindahl-Hirschman Index (HHI), all crops and sugarcane crop (planted area), by municipality, 2021.

Source: Own elaboration based on data [7, 15].

Note: Intervals use Natural Breaks (Jenks) methodology, ArcGIS version 10.7.

## 3.4 Spatial Autocorrelation (Moran's I), 2021

In accordance with the theoretical principles of Moran's I and taking into account that the *p-value* is equal to 0.0000001 with a *z* parameter equal to 32.840635 that represents the standard deviation, the null hypothesis (Ho) that establishes that the values of the entities (polygons in the map) are randomly distributed is rejected, and it is identified that there is less than a 1% probability that this grouping pattern could be the result of chance. Consequently, it is validated that in 2021, sugarcane production in the Colombia at the municipal level yields a Moran's I of 0.093997, which allows establishing an *agglomeration* of the variable in groups of municipalities where there is a correlation of spatial contiguity that identifies a cluster structure (Figure 7).

On the other hand, doing the *High-Low Clustering Report* that makes an analysis using the *Getis and Ord's G index*, it is possible to identify the degree to which municipal units with high (hotspots) or low (coldspots) values are grouped together, i.e., a prioritization of cluster formation can be found [23].

Additionally, it is possible to find three types of sugarcane productive agglomerations: 1) *high- productivity agglomeration* located towards the west of the country in the departments of Valle del Cauca, Cauca and Tolima; 2) *medium-productivity agglomeration* located in the departments of Santander, Norte de Santander, Antioquia and Meta; 3) *low-productivity agglomeration* distributed in the municipalities of southern Chocó, and the departments of Cauca, Huila, Valle del Cauca, Caquetá, and Meta (see Figure 7).

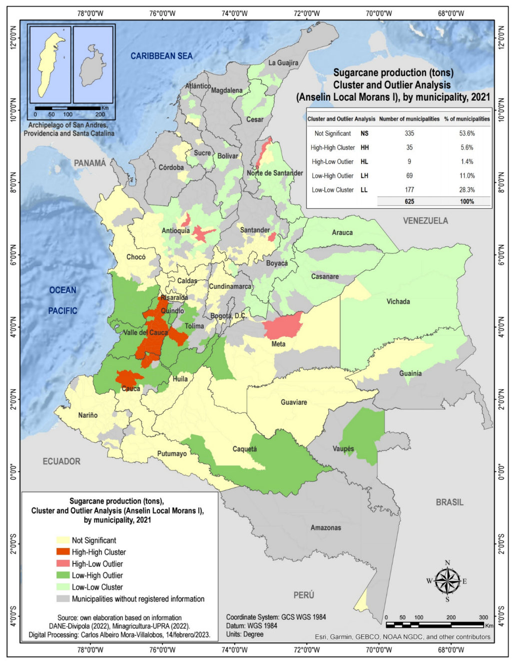



**Figure 7.** Cluster and Outlier Analysis (Anselin Local Moran's I), sugarcane production (tons) by municipality, 2021.

Source: Own elaboration based on data [7, 15].

## 3.5 Sugarcane Production and Multidimensional Poverty (PMI) in Populated Rural Centres and Dispersed Rural Areas (PRCDRA), 2018

In this section, DANE [18] database is taken, which is the only one that shows the MPI disaggregated at the municipal level for the 1,121 municipalities in the country. In 2018, the percentage of people in multidimensional poverty in the Colombia was 19.6% of the national total, 13.8% in *municipal urban areas* and 39.9% in PRCDRA;

that is to say, the percentage of people in multidimensional poverty in PRCDRA was 2.9 times that of the municipal urban areas [25].

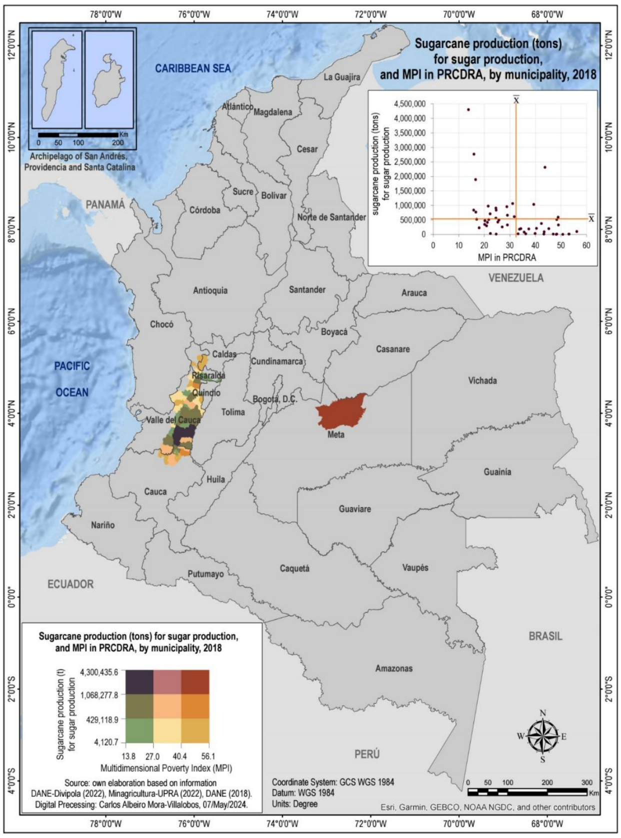
In 2018, the national agricultural production was 54.6 million tons, where sugarcane accounted for 55.2%, followed by 'plátano'—*Musa x paradisiaca* (8.1%), cassava—*Manihot esculenta* (4.7%), potato—*Solanum tuberosum* (4.1%) and banana - *Musa x paradisiaca* (3.8%), which allows us to identify the importance of sugarcane production for the Colombian agricultural economy. Sugarcane production is destined for three uses: sugar production, panela production and honey production.

Using the database DANE [18], the essay took only the sugarcane production municipalities in 2018, and found that in that year Colombia produced 30.2 million tons of sugarcane, of which, 28.7 million tons were for sugar production (95.3%) distributed in 51 municipalities; 1.3 million tons were for panela production (4.5%) distributed in 553 municipalities; and 21,978 tons were for honey production (0.1%) distributed in 56 municipalities [17]. According to MPI data, the incidence of multidimensional poverty in the population located in PRCDRA of the 615 sugarcane producing municipalities was on average 26.3%, with the maximum being 98.9% and the minimum 0.1%. Table 4 shows that only 15 municipalities had multidimensional poverty of less than 20% [18]. Additionally, it could be eastablished that the variables with the highest incidence were: *informal work* (average 91.1%, maximum 98.9% and minimum 69.9%); *low educational achievement* (average 80.9%, maximum 96.7% and minimum 27.5%); and *without access to improved water sources* (average 45.9%, maximum 97.0% and minimum 0.4%) [18]. Performing a disaggregation according to final destination of sugarcane production, it was found that:

- *Sugarcane production for sugar production*: 51 producing municipalities with average MPI in PRCDRA of 19.7% (minimum 0.1% and maximum 94.4%). The variables with the highest incidence were *informal work*, *low educational achievement* and *long-term unemployment* (see Figure 8a).
- *Sugarcane production for panela production*: 553 producing municipalities with average MPI in PRCDRA of 26.5% (minimum 0.1% and maximum 98.9%). The variables with the highest incidence were *informal work*, *low educational achievement* and *without access to improved water sources* (see Figure 8b).
- *Sugarcane production for honey production*: 56 producing municipalities with average MPI in PRCDRA of 27.4% (minimum 0.1% and maximum 98.3%). The variables with the highest incidence were: *informal work*, *low educational achievement* and *long-term unemployment* (see Figure 8c).

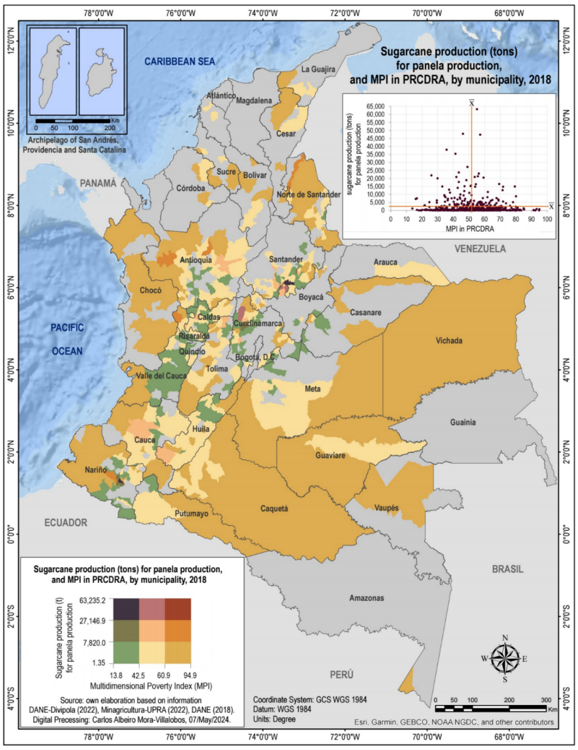
Although sugarcane has traditionally been a distinctive activity of Colombian agricultural production, the essay identifies that it does not significantly contribute to improving the quality of life of rural residents in the variables reflected by the MPI.

In this section the correlational hypothesis proposed in this work have been tested:

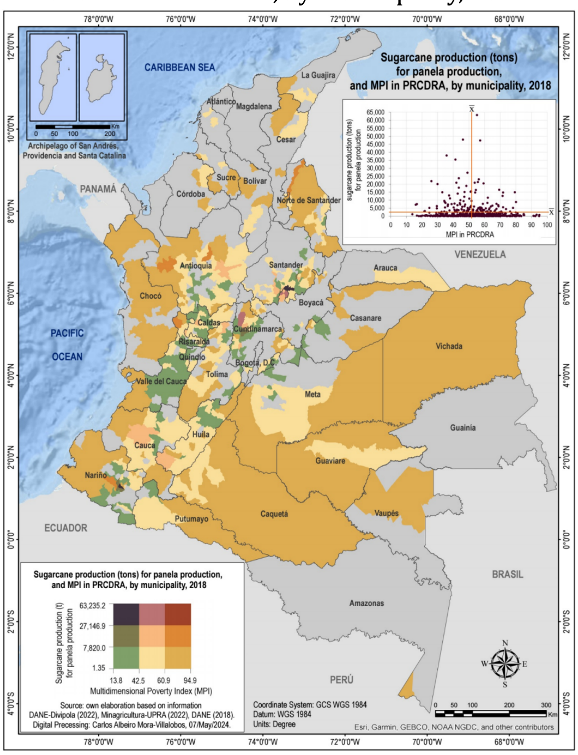



(**a**) Sugarcane production (tons) for sugar production and MPI in PRCDRA, by municipality, 2018

**Figure 8.** *Cont.*




(**b**) Sugarcane production (tons) for panela production and MPI in PRCDRA, by municipality, 2018




(**c**) Sugarcane production (tons) for honey production and MPI in PRCDRA, by municipality, 2018

**Figure 8.** Sugarcane production (tons) and Multidimensional Poverty Index (MPI) in populated rural centres and dispersed rural areas (PRCDRA), according to production destination, by municipality, 2018.
Source: Own elaboration based on data [17, 18].
Note: Intervals use Geometrical Interval methodology, ArcGIS version 10.7.

**H1**: There is an inverse association between sugarcane production and the incidence of multidimensional poverty in the *populated rural centres and dispersed rural areas* of sugarcane production municipalities, which indicates that municipalities with higher sugarcane production have lower rates of multidimensional poverty in *populated rural centres and dispersed rural areas*.

This hypothesis test is validated separately for each of the three destinations of sugarcane production (sugar, panela and honey production).

Taking into account the three uses of sugarcane, the information was classified according to production destination (sugar, panela and honey). For this, a data panel is created for the sugarcane producing municipalities in 2018, and subsequently, found Spearman's correlation for 4 variables: 1) percentage of population with multidimensional poverty (MPI) in *populated rural centres and dispersed rural areas* (MPI_PRCDRA); 2) percentage of participation municipality in national sugarcane production according to production destination for sugar (Produ%Sugar), panela (Produ%panela) and honey (Produ%honey); 3) LQ of sugarcane production according to production destination (LQsugar, LQpanela, LQhoney); and 4) section of the HHI representing sugar crop (planted area) according to crop destination (HHIsugar, HHIpanela, HHIhoney) (see Table 5).

The normality of the variables was evaluated using the *Kolmogorov-Smirnov test* ($p > 0.05$), while the test results indicated that the variables do not have a normal distribution ($p < 0.05$). Thus, *Spearman's correlation method* was selected because it is robust to evaluate association of variables when the data does not meet the assumptions of normality; in addition, because it evaluates the monotonic relationship between two variables (when one variable increases, the other variable also increases or decreases, but not necessarily at a constant rate).

Considering the results in Table 4, the following inferences are obtained:

- *Sugarcane production for sugarproduction*: H1 is accepted and H0 is rejected because the correlation between the variables is high, a inverse association is identified, and the *p-values* are less than the significance level of 0.05, indicating that the

**Table 4.** Incidence of multidimensional poverty in sugarcane production municipalities, 2018.

| | **Sugarcane Production (according to production destination)** | | | | | |
|---|---|---|---|---|---|---|
| | **Sugar production** | | **Panela production** | | **Honey production** | |
| **Percentage of population living in multi-dimensional poverty** | **Number of municipalities** | **Percentage of municipalities** | **Number of municipalities** | **Percentage of municipalities** | **Number of municipalities** | **Percentage of municipalities** |
| 0.0–20.0% | 7 | 13.7% | 7 | 1.3% | 1 | 1.8% |
| 20.1–40.0% | 28 | 54.9% | 104 | 18.8% | 8 | 14.3% |
| 40.1–60.0% | 16 | 31.4% | 277 | 50.1% | 30 | 53.6% |
| 60.1–80.0% | 0 | 0.0% | 92 | 16.6% | 13 | 23.2% |
| 80.1–100% | 0 | 0.0% | 73 | 13.2% | 4 | 7.1% |
| | **51** | **100.0%** | **553** | **100.0%** | **56** | **100.0%** |

Source: Own elaboration based on data [17, 18].

**Table 5.** Spearman correlations in pairs by municipality, 2018.

| **Sample 1** | **Sample 2** | **N** | **Correlation** | **95% Confidence interval (CI) for ρ** | ***p-value*** |
|---|---|---|---|---|---|
| Produ%Sugar | MPI_PRCDRA | 51 | −0.558 | (−0.732; −0.315) | 0.000 |
| LQsugar | MPI_PRCDRA | 51 | −0.690 | (−0.822; −0.488) | 0.000 |
| HHIsugar | MPI_PRCDRA | 51 | −0.727 | (−0.845; −0.540) | 0.000 |
| LQsugar | Produ%Sugar | 51 | 0.823 | (0.685; 0.904) | 0.000 |
| HHIsugar | Produ%Sugar | 51 | 0.854 | (0.735; 0.922) | 0.000 |
| HHIsugar | LQsugar | 51 | 0.980 | (0.961; 0.990) | 0.000 |
| Produ%Panela | MPI_PRCDRA | 553 | −0.052 | (−0.135; 0.031) | 0.219 |
| LQpanela | MPI_PRCDRA | 553 | 0.054 | (−0.030; 0.137) | 0.207 |
| HHIpanela | MPI_PRCDRA | 553 | −0.006 | (−0.089; 0.077) | 0.885 |
| LQpanela | Produ%Panela | 553 | 0.736 | (0.690; 0.777) | 0.000 |
| HHIpanela | Produ%panela | 553 | 0.712 | (0.663; 0.755) | 0.000 |
| HHIpanela | LQpanela | 553 | 0.909 | (0.890; 0.925) | 0.000 |
| Produ%Honey | MPI_PRCDRA | 56 | −0.086 | (−0.342; 0.181) | 0.528 |
| LQhoney | MPI_PRCDRA | 56 | −0.214 | (−0.454; 0.055) | 0.114 |
| HHIhoney | MPI_PRCDRA | 56 | −0.144 | (−0.393; 0.125) | 0.290 |
| LQhoney | Produ%Honey | 56 | 0.563 | (0.334; 0.729) | 0.000 |
| HHIhoney | Produ%honey | 56 | 0.568 | (0.340; 0.733) | 0.000 |
| HHIhoney | LQhoney | 56 | 0.816 | (0.682; 0.897) | 0.000 |

Source: Own elaboration based on data [17, 18].

Spearman correlation coefficients are statistically significant.

- *Sugarcane production for panela production*: Ho is accepted and H1 is rejected because the correlation between the variables is very low, the type of association between the variables (positive or negative) is not clearly identified, and the *p-values* are higher than the significance level of 0.05, indicating that the Spearman correlation coefficients are not statistically significant.
- *Sugarcane production for honey production*: Ho is accepted and H1 is rejected because the correlation between the variables is low, although an inverse relationship between the variables is identified, and the *p-values* are higher than the significance level of 0.05, indicating that the Spearman correlation coefficients are not statistically significant.

For the reasons presented, it is only possible to validate the inverse relationship between sugarcane production for sugarproduction, volume specialization (LQ) and specialization by planted area (HHI), with respect to the incidence of multidimensional poverty in the rural areas of sugarcane producing municipalities (MPI_PRCDRA).In the case of sugarcane for production panela and honey, it was not possible to establish such a relationship.

## 4. Discussion

This study used the Gini coefficient to observe the concentration of sugarcane production, LQ and HHI to identify specialization of production and Moran index to establish agglomeration, being methodologies widely used for these purposes as shown in previous studies by Cosrojas and Eguia [26], Kartikawati et al. [27], Castro and Fuentes [8], Schouten and Heijman [9], and Chasco Yrigoyen [28]. Our analysis of the agglomeration of sugarcane production by municipalities, and subsequently, the contrast with multidimensional poverty, noticed high rates of MPI in rural sugarcane productive areas.This finding constitutes a challenge for guilds institutions and rural development policymakers, especially for producer sugarcane for panela production.

It is highlighted that productive agglomeration requires elements of the *value chain* to convert *comparative advantages* into *competitive advantages*, and in this way, create *agroindustrial clusters* (CAI) that include transformation and value addition processes, complementary to the *agricultural cluster* (AC). The main challenge for developing countries is to transform CAs into CAIs [13]. This study focused on sugarcane production to find the productive agglomeration (agricultural cluster); therefore, a next stage should analyze the sugarcane value chain, especially in municipalities where there are agglomerations. This study would allow reality and theory to be contrasted within the framework of what the FAO has defined as *agricultural-based clusters* (ABCs) [11].

The agglomeration of sugarcane production is strongly localized; therefore, the business fabric (horizontal/vertical) must be studied to promote innovation processes, generate new commercial relationships and support small and medium-sized agroproductive companies. For this, it is necessary to implement *regional innovation systems* (RIS), which contribute to maintaining, improving and consolidating production in the medium and long term.

Sugarcane production has economic importance, and additionally, it is a source of food for the Colombian population (especially panela sugarcane). Therefore, it is necessary to seek mechanisms that guarantee generational change and improve the economic conditions of marketing, especially in regions where small and medium-scale sugarcane production is maintained. On the other hand, Lagos-Burbano and Castro-Rincón [29] argue that the economic importance of sugar cane lies in the growing demand for the raw material for agroindustrial production. Additionally, the byproducts are used in the production of flour, blocks and silages for livestock feed. Likewise, sugarcane bagasse has traditionally been a raw material for the production of paper and the production of energy in the boilers of sugar mills [30].

## 5. Conclusions

In 2021, there were 625 sugarcane producing municipalities, of which 100 concentrate 90.1% of the total production, Palmira (11.2%), Candelaria (6.2%), El Cerrito (4.8%) standing out, Guacarí (3.9%), Florida (3.0%), Bugalagrande (3.0%), Zarzal (2.9%) and Pradera (2.7%). The measurement of the departmental concentration of sugarcane production allowed us to show a Gini coefficient of 0.932 in 2007, 0.929 in 2014 and 0.846 in 2021. Likewise, it was possible to establish that at the municipal level there is a much higher concentration of production, with slight decrease from a Gini of 0.973 in 2007, to 0.972 in 2014 and 0.932 for 2021.

For its part, the measurement of productive specialization through LQ found that sugarcane production is strongly clustered in Valle del Cauca, Cauca, Santander, Boyacá, Cundinamarca and Antioquia. Likewise, there are 255 municipalities where sugarcane represented more than 50% of agricultural production, among which Útica (99.9%) and La Peña (99.1%) in Cundinamarca standing out; Candelaria (99.7%), Zarzal (99.6%), Palmira (99.6%), Pradera (99.5%), El Cerrito (99.4%), Cali (99.3%) and Guacarí (99.2%) in Valle del Cauca; Padilla (99.8%), Villa Rica (99.6%) and Miranda (99.4%) in Cauca; and San José de Pare (99.6%) and Chitaraque (99.4%) in Boyacá.

On the other hand, the Moran index identified that sugarcane production at the municipal level tends to agglomerate. Three types of clusters werefound: 1) *high agglomeration* located in the west of the country between the departments of Valle del Cauca, Cauca and

Tolima; 2) *medium agglomeration* located in the departments of Meta, Antioquia, Santander and Norte de Santander; and 3) *low agglomeration* distributed in the southern municipalities of Chocó, Valle del Cauca, Cauca, Huila, Tolima and Caquetá. In addition, it is possible to identify that sugar cane producers are densely concentrated, while panelera and honey cane producers tend to be smaller and more atomized.

Additionally, it is important to highlight that in 2021 Colombia was the seventh largest sugarcane producer in the world after Brazil, India, China, Pakistan, Thailand and Mexico, confirming the economic importance of sugarcane production for the national GDP. Therefore, it is necessary to continue studying sugarcane as a product of economic importance for the Colombian agricultural production, addressing other aspects related to the articulation of the value chain, the impacts of climate change, the contribution of the planted area in the absorption of $CO_2$, the management of pests and diseases with biological control mechanisms and agroecological fertilizers, the valorization of territories, entrepreneurship and the formalization of agricultural SMEs related to sugarcane, including the production of organic sugarcane and other varied topics.

## Author Contributions

Carlos Albeiro Mora-Villalobos: principal researcher (statistical analysis of data, elaboration of tables and figures, elaboration of thematic cartography, writing of the paper). Jaime Alberto Rendon Acevedo: senior researcher (statistical analysis of data, writing of the paper, revision of the final paper, approval of the manuscript for submission to RWAE).

## Data Availability

The authors confirm that the data used for this study can be consulted and downloaded freely on the websites of the official institutions cited in the methodology of this study.

## Conflicts of Interest

The authors have no conflict of interest related to this document.

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## Note

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