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RESEARCH ARTICLE

Analysis of the Concentration and Specialization of Vegetable Production in Colombian Municipalities between 2007 and 2021

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ABSTRACT

In 2021, vegetable crops in Colombia accounted for 3.7% of national agricultural production, reaching a total production of 2.71 million tons, of which 81.2% came from 8 departments, the most representative being Boyacá (20.3%), Antioquia (17.3%), Cundinamarca (12.0%), Nariño (8.1%) and Santander (7.4%). Of the country's 1,121 municipalities, 796 reported vegetable production. This article aims to analyze the concentration and specialization of vegetable production in Colombian municipalities between 2007–2021. The methodology analyzed two statistical databases applying the Gini coefficient, Location Coefficient (LQ), Herfindahl-Hirschman Index (HHI) and Moran's index of spatial autocorrelation to identify the agricultural clusters (CA) in the Colombian vegetables sector, which are complemented with thematic cartography. Measurements were made in 2007, 2014 and 2021 (start–mid–end). Additionally, the sensitivity of five vegetable crops (the most important for national production) is estimated using OLS, with respect to the average annual temperature (AAT) and total annual precipitation (TAP). The results reveal a regional Gini of 0.7496, 0.7674 and 0.7072 in 2007, 2014 and 2021, respectively. By 2021, 398 municipalities were identified with LQ greater than 1.0, of which 66 were among the 20% of the highest values (between 12.03 and 27.02). Likewise, 51 municipalities were found where vegetables accounted for more than 50% of total agricultural production. Additionally, in 2021, the municipalities with the highest level of specialization

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HHI were Sáchica (1.00), Cajicá (0.77), Aquitania (0.65), Tibasosa (0.605) and Cota (0.619). The OLS between production, AAT and TAP identified statistical significance only in tomato and green onion. In conclusion, the findings indicate a significant regional concentration of vegetable production in the last fifteen years. A variation of 34.7% in the number of producing municipalities was observed at the between 2007 and 2021. The most representative crops in the years analyzed were tomato, green onion, bulb onion and carrot, which in 2021 were 64.0% of national production. These results contribute to the guilds institutions, regional governments, municipal administrations, and public policymakers because they constitute an input to regional productive planning in rural areas, especially where peasant family farming is prevalent.

Keywords: Vegetables; Agricultural Clusters; Productive Concentration; Productive Specialization

1. Introduction

Vegetables are a group of plants generally grown in gardens or irrigated fields, which are consumed as food in raw or prepared form and include various green legumes such as beans and peas. The distinction of vegetables is arbitrary and is not based on any basis of botanical classification. For example, tomatoes and peppers are considered vegetables (not fruits), even though the edible part is a fruit. Most vegetables are rich in fiber, water content (approximately 80% by weight), potassium, calcium, iron, and vitamins A, C, E, and K [1, 2]. Among the best-known crops are chard, celery, spinach, eggplant, lettuce, bell pepper, radish, tomatoes, onion, carrot, beet, potato and parsley, among others.

On the other hand, the Horticultural Association of Colombia (Asohofrucol) is a trade and agribusiness organization founded in 1994 as a non-profit agricultural society under private law, which seeks to strengthen and boost the development of the fruit and vegetable subsector. The association represents the interests of more than 43 thousand producers involved in the production and marketing of fruits and vegetables, seeking to promote the productive and competitive improvement of their agribusinesses, as well as to contribute to the integral rural development of the country [3]. Likewise, the Rural Agricultural Planning Unit (UPRA) of the Ministry of Agriculture and Rural Development (Minagricultura) is the institution responsible for the quantification, follow-up and publication of the Municipal Agricultural Evaluations (EVA), which are statistical records that show area planted, area harvested, production and yield of national agricultural production [4].

According to statistical information from Minagricultura-UPRA [5], in 2021, the country registered 5.38 million hectares (ha) cultivated where vegetables represented 2.35% equivalent to 126,809.9 ha cultivated, with a harvested area of 120,528.4 ha, and total production of 2.71 million tons (t) and national average yield of 22.5 t ha^{-1}. Similarly, by 2021, 30 vegetable crops were recorded, of which seven accounted for 82.1% of national production: tomato (31.4%), green onion (12.6%), carrot (10.2%), bulb onion (9.9%), watermelon (8.6%), pumpkin (5.1%) and lettuce (4.4%).

However, environmental conditions, the dynamics of regional wholesale markets and the productive diversification of agriculture in the regions have changed considerably in the last 30 years. Therefore, it is necessary to identify the departments and municipalities that currently constitute the spearhead of vegetable production in terms of volume and agronomic yields. Currently, there are several transformations that can be observed in the processes of planting, harvesting and marketing of vegetables, especially because in recent years, new food trends have appeared that are related to the preference for fresh foods, where a growing market for organically produced vegetables is identified, e.g., cleaner agriculture [6], homemade food and comfort food [7, 8], realfooding [9], food storytelling and from land to table [10], slow food [11, 12], healthy snacks [13], and others.

This document seeks to provide technical information that contributes to the strategic planning of value chains related to vegetables, taking into account that Colombian horticultural production is characterized by being heterogeneous, fragmented, generally cultivated on small tracts of land that on average range from 1 and

2 hectares, which are managed through the production of peasant family agriculture, where peas, tomato, bighead onion, green onion, potato, carrot and string bean crops stand out [14, 15]. In this sense, this work is presented as a descriptive text that, through the application of statistical methodologies, allows the identification of intertemporal regional changes in the production of vegetables in Colombia. It is expected to serve as a source of information for those who are interested in carrying out research projects and need a reference for decision-making in the field of production, especially for growers, agricultural public policymakers, and public institutions that need to evaluate the municipal potential in terms of vegetable production.

Considering that in 2021, 71% of the Colombian municipalities recorded vegetable production, and that 80% of national production was concentrated in 143 municipalities (12.8% of the total), two questions arise: which are the municipalities with the highest level of specialization in vegetable production?, and do agricultural clusters exist in Colombian vegetable production? In this sense, the objective of this article is to analyze the concentration and specialization of vegetable production in Colombian municipalities between 2007 and 2021, by applying the Gini coefficient, location coefficient (LQ), Herfindahl-Hirschman Index (HHI) and autocorrelation by Moran's index, to identify the agricultural clusters (CA) of vegetables in Colombia. The measurements were carried out mainly for 2007, 2014 and 2021 (start–mid–end). The period 2007 to 2021 was selected due to the availability of statistical information in institutional sources. In this work, LQ measures specialization through the volume of annual municipal vegetable production in tons. In contrast, HHI measures specialization according to the annual amount of land cultivated with vegetables (area planted) in the municipalities. Additionally, the document provides thematic cartography at municipal scale to visualize the spatial distribution of production, agronomic yield (t ha^{-1}), LQ, HHI and Moran's index.

With respect, for concentration measurements, the Gini coefficient and the Lorenz curve have traditionally been implemented [16], while for the measurement of productive specialization, the location coefficient (LQ) is used [17, 18]. According to Castro and Fuentes [16], there is valuable evidence on economic concentration and specialization in industrial activities, however, there is not so much evidence that can address the issue of agricultural activities. This work provides essential information on the concentration and specialization of vegetable production in the municipalities of Colombia.

On the other hand, although Colombia has always produced good fresh food (fruits, vegetables, and greens), climate change can impact agricultural productivity and generate adverse economic and social effects. In this regard, Cortés-Cataño et al. [19] evaluated the impact of some environmental variables on the production of the most representative crops (coffee, rice, palm oil, sugarcane, and corn) using data from the 1121 municipalities from 2007 to 2020; but do not make any specific comments on vegetable production. For its part, Erayya et al. [20] warn that changing climate may cause adverse effect on crops and agricultural production, and also on occurrence, severity and spread of plant diseases. Emerging crop diseases seriously threaten crop production, especially for short-cycle crops. Additionally, Ospina et al. [21] shows that environmental pollution from irrigation systems it can severely affect the quality vegetable crops in areas of high productive concentration (such as the Bogotá savannah). This study concludes that it is necessary to inform stakeholders (farmers, markers, consumers and regulatory entities), to carry out analyses that guarantee the quality and safety of vegetables throughout the production chain based on Good Agricultural Practices (GAPs). Apart from that, Neme et al. [22] study the impact of Contract Farming (CF) on income of smallholder vegetables farmers in the Central Rift Valley of Ethiopia. The result shows that the proportion of total crop area allocated to vegetables, access to credit, frequency of extension contacts, market information, and distance of the market center have positive and significance effects on the decision of vegetable producers to participate on the CF. The topics discussed above (climate change, phytopathological risks, irrigation, fertilization and soils, quality and safety, new production techniques, farmers' income, marketing methods, new consumer trends, among others), it is current topics of interest for the study of vegetable production.

The conceptual framework of this work supports the idea of *agricultural clusters* proposed by FAO [23], consequently, agriculture in the 21st century must achieve higher levels of productivity, so the agricultural sector needs new tools to improve competitiveness and the capacity to disseminate and adopt new technologies; for this reason, agro-based clusters (ABCs) are a sectoral organization tool that must be promoted and coupled with government institutions and public policies [23]. 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" [24]. Additionally, Otsuka and Ali [25] classify ABCs by making a distinction between agricultural clusters (AC) that market fresh produce without strict grading and processing, and agro-industrial clusters (AIC) that include value-added-oriented transformation processes to meet market requirements. The main challenge for developing countries is to dynamize ABCs and transform their ACs into AICs [25].

Additionally, the ABCs contribute to articulating the value chain actors, promoting innovation and competitiveness, vertical and horizontal linkages between local agricultural enterprises, and relations with support organizations (local governments, research institutions, financial institutions, training centers, among others) [23]. ABC analysis is a necessity for the contemporary agricultural economy [26]. This work provides relevant information on the AC of vegetables at the municipal level.

Finally, the results of this work aim to contribute to the study of the Colombian agrarian and regional economy, where vegetable production is a representative factor of rural development, food and nutrition security, rural household labor and incomes, the culture and agricultural vocation of the country, especially for the peasant family agriculture, as well for the diffusion of agricultural innovation and technology. This article is the first to interrelate the Gini coefficient, LQ and HHI with municipal vegetable production 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 present results; subsequently, section four is a discussion and section five conclusions.

2. Materials and Methods

2.1. Description of the Study Area

The political-administrative division of Colombia prepared by the National Administrative Department of Statistics (DANE), shows that the country has 32 Departments (regions) and 1,121 municipalities (1,102 municipalities, San Andres Island and 18 non-municipalized areas—ANM) [27]. Official layers (shp) of the Geoportal of the Agustín Codazzi Geographic Institute [28] are used to prepare the thematic cartography.

2.2. Data and Study Variables

Two statistical databases were used:

- Report of the Municipal Agricultural and Livestock Evaluations (EVA) [Agricultural Base EVA from 2019 to 2021—Publication date 22042022], from the Agricultural Rural Planning Unit and the Ministry of Agriculture and Rural Development [5];
- Report of the Municipal Agricultural and Livestock Evaluations (EVA) [Agricultural Base EVA 2007–2018 (P)_12_02_2020], from the Agricultural Rural Planning Unit and the Ministry of Agriculture and Rural Development [29].

The two databases encompass comprehensive statistical data pertaining to 1,121 municipalities. This data includes information on the extent of planted area (measured in hectares—ha), harvested area (ha), production (measured in tons), and yields (t ha^{-1}) for 150 crops grouped into 8 typologies: cereals, fruits, vegetables, legumes, oilseeds, roots and tubers, traditional tropical crops, and crops for condiments and medicinal and aromatic beverages. The time period 2007 to 2021 was selected due to the availability of statistical information in institutional sources.

Database of the Institute of Hydrology, Meteorology and Environmental Studies – IDEAM [30], containing temperature and precipitation measurements between

2007 and 2021. We selected the meteorological stations located in the vegetable production municipalities. Subsequently, we formed a data panel with the average annual temperature (AAT) and total annual precipitation (TAP) of daily data between 01/January/2007 and 31/December/2021.

2.3. Data Analysis Techniques

The statistical information is analyzed in four stages:

- Vegetable production in Colombia between 2007 and 2021: descriptive statistics are applied to make a first analysis of the data at the departmental and municipal levels. This analysis is applied for the years 2007, 2014 and 2021 (start–mid–end). Between 2007 and 2018, the measurements of planted area, harvested area and agricultural production in Colombia were made using a methodology that included twelve crop groups: cereals, vegetables, legumes, other transitory crops, flowers and foliage, fibers, fruits, oilseeds, tubers and bananas, forestry, other permanent crops, and aromatic, condimentary and medicinal plants. As of 2019, the using methodology that included eight crop groups: cereals, vegetables, legumes, fruits, oilseeds, tubers and bananas, traditional tropical crops, and crops for condiments and medicinal and aromatic drinks.
- Concentration of vegetable production: the Gini coefficient is applied at the departmental and municipal levels for 2007, 2014 and 2021 (start–mid–end). 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, a graphical way of showing the distribution of the variable[31]. It is necessary to mention that agricultural production is strongly determined by environmental and geographic conditions, and therefore, the Gini identifies the concentration of vegetables production but does not take into account environmental and geographic factors.
- Specialization of vegetable production in the municipalities: the Location Quotient (LQ) is applied at the municipal level for 2007 and 2021, with 12 and 8 crop groups, respectively. LQ quantifies the density of a variable or economic activity in a region concerning the national total, revealing the productive activities with comparative advantage[17, 32]. Specifically, LQ is a comparative relationship between a locality and a more extensive reference region concerning a specific variable, being the most commonly used methodology to identify clusters[32]. 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. In contrast, LQ greater than 1.0 indicates a high level of relative specialization of the region in the variable under study concerning national production, and vice versa[33]. 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 production of vegetables (1) in municipality *j*; E_i is the production of vegetables (2) in Colombia; E^j is the total agricultural production in municipality *j*; *E* corresponds to the total agricultural production in Colombia[17, 33, 34].

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

$$\mathrm{HHI}_j = \sum_{h=1}^{H}\left(\frac{L_{jh}}{L_j}\right)^2 = \sum_{\cdot}\left(\frac{L_{jh1}}{L_j}\right)^2 + \left(\frac{L_{jh2}}{L_j}\right)^2 + \left(\frac{L_{jh3}}{L_j}\right)^2 + \cdots + \left(\frac{L_{jH}}{L_j}\right)^2 \tag{2}$$

Where: L_{jh} is the amount of cultivated land (planted area) dedicated to crop group *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 crop groups present in municipality *j*. Note that if all the land in a municipality is dedicated to a single crop group, then the specialization index HHI_j is equal to unity (HHI_j = 1); therefore, the greater the number of crop groups present in a municipality, the lower is the value of HHI_j[34, 35]. 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 crop groups present in the municipality. This study focused attention exclusively on vegetable cultivation, therefore, specialization should be understood as the preference of farmers in municipality *j* to have the most significant amount of available land cultivated with vegetables, which are generally transitory crops (short cycle). This preference could result from the use of comparative advantages type geographical (height, temperature, precipitation and soil), and the proximity to the market. The measurements were made for 2007 and 2021, with 12 and 8 crop groups, respectively.

Spatial autocorrelation (Moran's I): 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 [34, 36]. We start from the null hypothesis (H_0) which states that the values of the polygons on the map are randomly distributed. When performing the statistical analysis, we have two parameters (p, z), where p represents a probability and whenever the value is small it allows us to reject the H_0. On the other hand, the z parameter represents the standard deviations, and usually, when it is tiny (close to zero), it indicates that there is not enough statistical evidence to reject the H_0; for this reason, z will always take very high values that can be positive or negative when the value of p is minimal [37].

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 values of p and z indicate the rejection of H_0, Moran's index greater than zero will indicate a tendency towards agglomeration, and conversely, if the index is less than zero, there is a tendency towards dispersion [37]. The measurements were only made for the year 2021.

Sensitivity analysis of vegetable crops to changes in temperature and precipitation: in this section, we build panel data to estimate an OLS by following the steps below:

- Taking the database Minagricultura-UPRA [5], selecting only the year 2021, we classify the crops according to production in tons from highest to lowest. From there, the group that represents 70% of the national vegetable production is arbitrarily selected.
- For each crop, the municipalities are classified according to production from highest to lowest, and then, the set of municipalities that represented 50% of the national production of the crop analyzed is arbitrarily taken.
- For each crop group and selected municipalities, a data panel is built between 2007 and 2021 that has the following variables: annual production of vegetables (according to crop), average annual temperature (AAT) and total annual precipitation (TAP) of daily data between 01/January/2007 and 31/December/2021. Temperature and precipitation data were taken from IDEAM [30]. In the municipalities that did not have a metrological station for recording temperature and precipitation (missing data), the "National Catalogue of Stations" was consulted, and data was taken from the "principal climate station" closest to the urban area of the municipality under study.
- To measure the sensitivity of vegetable crops to changes in temperature and precipitation, we proceeded to estimate the following OLS:

$$Q_{ji} = \beta_0 + \beta_1 AAT_i + \beta_2 TAP_i + \varepsilon \quad (3)$$

Where:

- Q_{ji} is the production in tons of vegetable crop *j* in municipality *i*.
- AAT_i is the average annual temperature of the meteorological station located in the municipality *i*.
- TAP_i is the total annual precipitation of the meteorological station located in the municipality *i*.
- β_1, β_2 are the coefficients that represent the sensitivity of the production of vegetable crop *j* with respect to each climatic variable.
- ε is the error term.

The OLS was processed in Stata software and has location fixed effects (municipality).

3. Results

3.1. Vegetables Production in Colombia between 2007 and 2021

According to statistical information from Minagricultura-UPRA [5], in 2021 the country registered 5.38 million hectares (ha) cultivated where vegetables represented 2.35% equivalent to 126,809.9 ha. Total vegetable production was 2.71 million tons (t) with a harvested area of 120,528.4 ha, reaching a national average yield of 22.5 t ha^{-1} (see **Figure 1**). Eight departments (25% of the country's regions) accounted for 81.2% of production: Boyacá (20.3%), Antioquia (17.3%), Cundinamarca (12.0%), Nariño (8.1%), Santander (7.4%), Norte de Santander (7.0%), Meta (5.0%) and Valle del Cauca (4.2%). Similarly, by 2021, 30 vegetable crops were recorded, of which 7 accounted for 82.1% of national production: tomato (31.4%) [*Lycopersicon esculentum*], green onion (12.6%) [*Allium fistulosum*], carrot (10.2%) [*Daucus carota*], bulb onion (9.9%) [*Allium cepa*], watermelon (8.6%) [*Citrullus lanatus*], pumpkin (5.1%) [*Cucurbita maxima*] and lettuce (4.4%) [*Lactuca sativa*] (see **Table 3**).

For 2014, statistical records show that the national planted area was 4.98 million ha, with a vegetable share of 1.63% and 81,431.6 ha planted, a production of 1.81 million tons and an average yield of 24.1 t ha^{-1}. In contrast, in 2007, the country had 4.47 million ha cultivated where vegetables represented 1.61% with 72,188.0 ha planted, a production of 1.55 million tons and an average yield of 23.2 t ha^{-1} (see **Table 1**). Longitudinally, the data allows calculating a total variation between 2007 and 2021 of 74.0% in vegetable production, 79.5% in harvested area and 75.7% in planted area. On the other hand, the data shows that in 2021, 95.0% of national vegetable production was concentrated in 15 departments. Additionally, it can be observed that as of 2010, the producing departments are divided into three large groups where Boyacá, Antioquia and Cundinamarca account for 49.5% of production, followed by Nariño, Santander and Norte de Santander (see **Figure 2**). **Table 2** shows the contrast of percentage changes in vegetable production between 2007–2021, grouped into three categories: outstanding increase, moderate increase and reduction. For his part, **Figures 3** and **4** spatialize the production and agronomic yields (t ha^{-1}) of the vegetables 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.

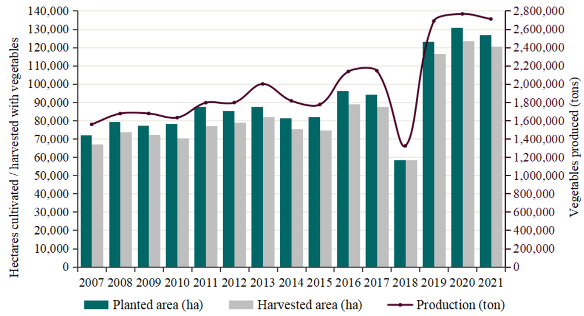


Figure 1. Area planted, area harvested and production of vegetables in Colombia, 2007–2021.

Source: Own elaboration based on data [5, 29].

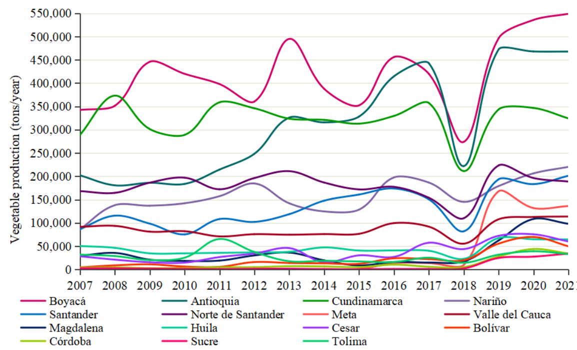


Figure 2. Vegetable production (t) by department: 2007–2021.

Source: Own elaboration based on data [5, 29].

On the other hand, by 2021, there were 796 municipalities that reported vegetable production of which 143 concentrated 80% of total production (see **Figure 3**). Aquitania (Boyacá) was the leading producer contributing 4.3% of national production, followed by Peñol (Antioquia) with 3.9%, San Martín (Meta) with 3.7%), Villa de Leyva (Boyacá) with 3.6% and Tona (Santander) with 3.1%. In 2014, 652 producing municipalities were registered, of which 109 concentrated 80% of total production, with Aquitania, Ocaña, El Santuario, Tibasosa and Tona having the highest percentage share. Comparatively, in 2007, there were 591 producing municipalities, of which 112 accounted for 80% of total production. The data show a percentage variation of 34.7% in the number of producing municipalities between 2007 and 2021, which indicates that vegetables have made

Table 1. Vegetable production (t) by department: 2007, 2014 and 2021.

	Production (t)					
	2007		2014		2021	
Department	**Tons**	**%**	**Tons**	**%**	**Tons**	**%**
Boyacá	342,356.0	22.0%	387,882.6	21.4%	548,879.7	20.3%
Antioquia	202,045.9	13.0%	315,790.6	17.4%	467,787.8	17.3%
Cundinamarca	288,827.4	18.5%	321,139.7	17.7%	324,354.3	12.0%
Nariño	86,121.4	5.5%	124,637.9	6.9%	220,258.3	8.1%
Santander	86,501.5	5.6%	147,616.9	8.1%	201,136.9	7.4%
Norte de Santander	168,187.1	10.8%	186,605.8	10.3%	188,760.8	7.0%
Meta	299.0	0.02%	1,048.8	0.1%	136,162.1	5.0%
Valle del Cauca	91,493.5	5.9%	75,958.7	4.2%	113,677.2	4.2%
Magdalena	29,286.0	1.9%	19,540.0	1.1%	98,055.4	3.6%
Huila	50,357.9	3.2%	47,285.9	2.6%	64,517.4	2.4%
Cesar	28,341.8	1.8%	15,214.0	0.8%	60,069.7	2.2%
Bolívar	4,566.5	0.3%	13,131.3	0.7%	49,822.1	1.8%
Córdoba	4,017.8	0.3%	6,500.7	0.4%	34,256.2	1.3%
Sucre	2,537.8	0.2%	546.7	0.03%	34,074.0	1.3%
Tolima	31,770.5	2.0%	18,554.8	1.0%	33,131.2	1.2%
Risaralda	44,509.0	2.9%	16,528.5	0.9%	26,327.4	1.0%
Cauca	15,729.3	1.0%	14,057.6	0.8%	25,763.3	1.0%
Caldas	56,902.3	3.7%	68,893.7	3.8%	23,190.0	0.9%
Atlántico	3,298.6	0.2%	7,145.9	0.4%	21,957.2	0.8%
La Guajira	8,510.5	0.5%	5,876.9	0.3%	17,574.3	0.6%
Quindío	9,473.0	0.6%	16,913.3	0.9%	9,783.7	0.4%
Casanare	-	-	792.6	0.04%	4,121.5	0.2%
Chocó	900.0	0.1%	2,084.0	0.1%	1,898.7	0.1%
Caquetá	-	-	183.5	0.01%	1,593.5	0.1%
Amazonas	435.0	0.03%	59.8	0.003%	988.1	0.04%
Putumayo	662.0	0.04%	335.2	0.02%	8808	0.03%
Vichada	109.0	0.01%	1,547.2	0.1%	351.8	0.01%
Guainía	-	-	66.4	0.004%	250.0	0.01%
Guaviare	54.4	0.003%	-	-	200.0	0.01%
Vaupés	17.0	0.001%	13.0	0.001%	162.7	0.01%
San Andrés Prov.Sta.Cat.	-	-	-	-	160.0	0.01%
Arauca	-	-	-	-	50.0	0.002%
	1,557,310.2	-	1,815,951.9	-	2,710,195.7	-

Source: Own elaboration based on data [5, 29].

inroads in municipalities where previously there were no such crops, and in several cases, in departments that are not traditionally producers (Meta, Casanare, Arauca, Vichada, Guainía, Guaviare, Caquetá, Córdoba, Sucre, Bolívar and Cesar).

Additionally, by 2021, 51 municipalities were identified where vegetables represent more than 50% of agricultural production, the most representative being: Sáchica (100%), Aquitania (94.5%), Villa de Leyva (94.3%), Guarne (93.2%) and Marinilla (92.6%). The problem with having an agricultural economy so specialized in vegetable production is that it is more exposed to risks that affect crops and harvests, derived from climate change, sudden price changes and the proliferation of pests or pathologies that could seriously affect crops, especially those that are not grown in greenhouses.

Moreover, contrasting production and agronomic yields (t ha^{-1}), it was observed that they do not always correspond positively (high–high). Given this situation, we proceeded to spatialize the variables in bivariate cartography to observe the location of the municipalities with higher production and higher yields. Thus, the mapping for 2021 shows that the municipalities with higher production and higher yields (t ha^{-1}) are located in Boyacá, Antioquia, Cundinamarca, Nariño y Santander (**Figures 3** and **4**).

3.2. Concentration of Vegetable Production

At the departmental level, it is crucial to note that vegetable production exhibits a high concentration, as indicated by the Gini index of 0.7496 in 2007, 0.7674 in 2014 and 0.7072 in 2021 (see **Figure 5a**). In general terms, it can be said that in 2021, 18.8% of Colombian departments are responsible for 75.0% of vegetable production.

Table 2. Percentage change in vegetable production (t) by department during 2007–2021.

Production (t)					
Outstanding Increase		**Moderate Increase**		**Reduction**	
Meta*	45,439.2%	Cauca	63.8%	Risaralda	−40.8%
Sucre*	1,242.7%	Boyacá	60.3%	Caldas	−59.2%
Bolívar*	991.0%	Putumayo	33.1%		
Vaupés	857.1%	Huila	28.1%		
Córdoba	752.6%	Valle del Cauca	24.2%		
Atlántico	565.7%	Cundinamarca	12.3%		
Guaviare	267.6%	Norte de Santander	12.2%		
Magdalena	234.8%	Tolima	4.3%		
Vichada	222.8%	Quindío	3.3%		
Nariño	155.8%				
Santander	132.5%				
Antioquia	131.5%				
Amazonas	127.1%				
Cesar	111.9%				
Chocó	111.0%				
La Guajira	106.5%				

Source: Own elaboration based on data [5, 29].

Note: The table does not include the departments of Arauca, San Andrés y Providencia, Casanare, Guainía and Caquetá because they did not report vegetable production in 2007. *: In the particular case of Meta, there was a considerable increase in the production of patilla (watermelon) which represented 90.9% of vegetables in 2021. In Sucre, there was a significant increase in the production of patilla and melon, which together accounted for 88.7% of vegetables. Bolívar increased its production of pumpkin, pumpkin, chili and melon, which accounted for 98% of vegetable production.

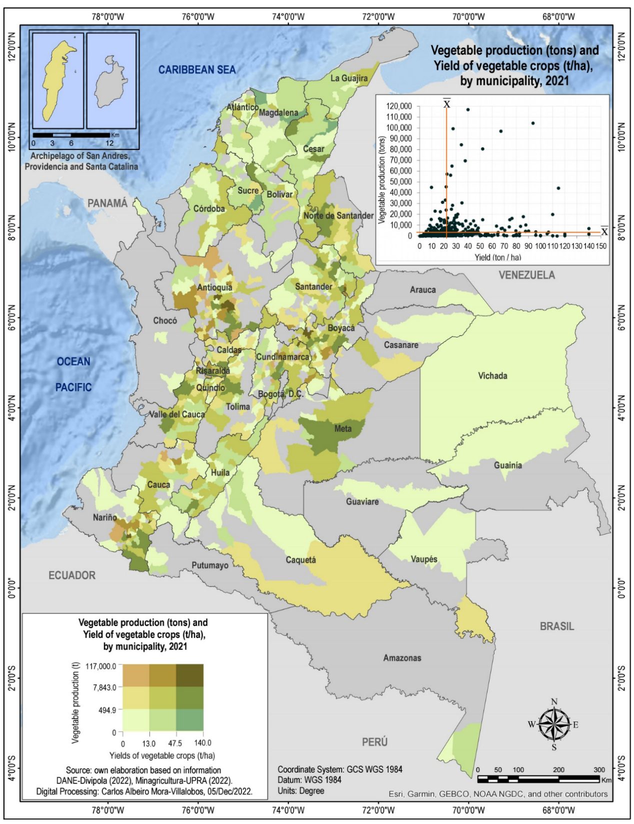


Figure 3. Vegetable production and yield (t ha^{-1}) by municipality, 2021.

Source: own elaboration based on data [5, 27].

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

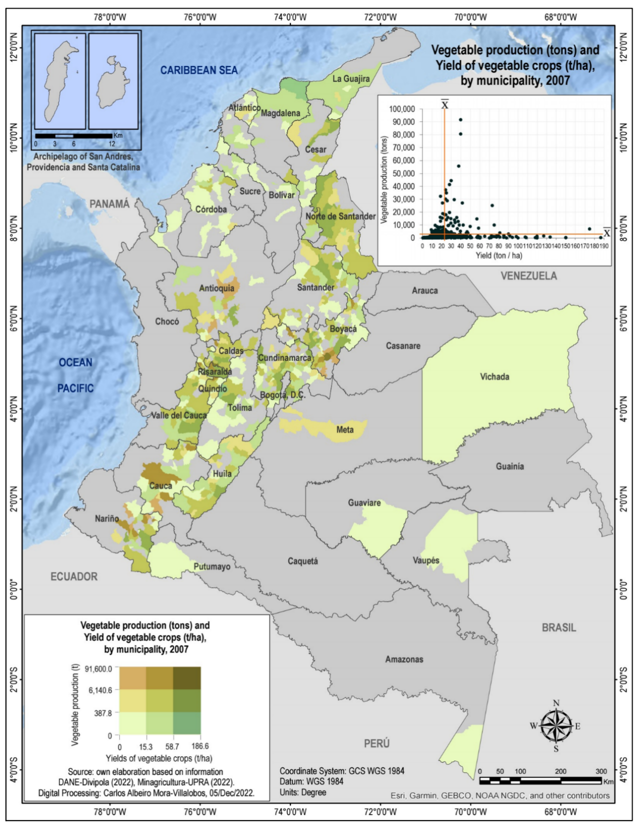


Figure 4. Vegetable production and yields (t ha^{-1}) by municipality, 2007.

Source: Own elaboration based on data [5, 27].

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

Table 3. Vegetable production (t) by crop: 2007, 2014 and 2021.

	Production (t)					
	2007		2014		2021	
Crop	**Tons**	**%**	**Tons**	**%**	**Tons**	**%**
Tomato	452,587.8	29.1%	609,980.0	33.6%	851,177.2	31.4%
Green onion	176,632.0	11.3%	222,318.2	12.2%	340,942.7	12.6%
Carrot	250,950.6	16.1%	219,702.8	12.1%	275,965.4	10.2%
Bulb onion	288,101.8	18.5%	253,219.4	13.9%	267,267.3	9.9%
Watermelon*	117,377.5	N.A	141,481.3	N.A	232,546.1	8.6%
Pumpkin	52,696.5	3.4%	102,693.3	5.7%	137,940.9	5.1%
Lettuce	35,105.6	2.3%	77,729.6	4.3%	119,266.4	4.4%
Other vegetables**	-	-	-	-	89,945.0	3.3%
Various vegetables**	9,088.3	0.6%	52,609.6	2.9%	-	-
Melon	-	-	-	-	73,455.4	2.7%
Paprika	44,590.3	2.9%	46,520.3	2.6%	67,242.0	2.5%
Cabbage	110,360.7	7.1%	62,115.3	3.4%	45,834.3	1.7%
Cilantro	12,872.0	0.8%	16,979.1	0.9%	36,496.9	1.3%
Chili	21,460.0	1.4%	23,174.3	1.3%	33,368.2	1.2%
Cucumber	15,386.5	1.0%	23,554.0	1.3%	29,421.7	1.1%
Beet	18,179.5	1.2%	26,319.4	1.4%	24,113.0	0.9%
Eggplant	4,920.4	0.3%	3,150.2	0.2%	15,556.3	0.6%
Broccoli	13,732.3	0.9%	14,574.4	0.8%	15,027.7	0.6%
Zucchini, Butternut pumpkin	2,175.6	0.1%	5,830.5	0.3%	13,567.9	0.5%
Celery	17,425.0	1.1%	7,788.6	0.4%	9,434.4	0.3%
Cauliflower	8,500.0	0.5%	9,878.0	0.5%	7,996.2	0.3%
Garlic	3,781.6	0.2%	8,666.6	0.5%	7,065.3	0.3%
Spinach	4,300.8	0.3%	7,788.5	0.4%	4,813.4	0.2%
Stewed cucumber	6,300.8	0.4%	3,351.1	0.2%	4,692.6	0.2%
Swiss chard	2,460.2	0.2%	1,952.6	0.1%	2,737.8	0.1%
Sweet potato	-	-	-	-	1,919.9	0.1%
Palm heart	662.0	0.04%	12,435.2	0.7%	880.8	0.03%
Guatila	-	-	2,125.0	0.1%	706.5	0.03%
Cabbage	2,595.0	0.2%	391.0	0.02%	324.1	0.01%
Asparagus	2,216.5	0.1%	69.0	0.004%	314.0	0.01%
Radish	108.7	0.01%	366.0	0.02%	176.8	0.01%
Chives	-	-	480.0	0.03%	-	-
Leek	120.0	0.01%	160.0	0.01%	-	-
Turnip	-	-	30.0	0.002%	-	-
	1,557,310.2	-	1,815,951.9	-	2,710,195.7	-

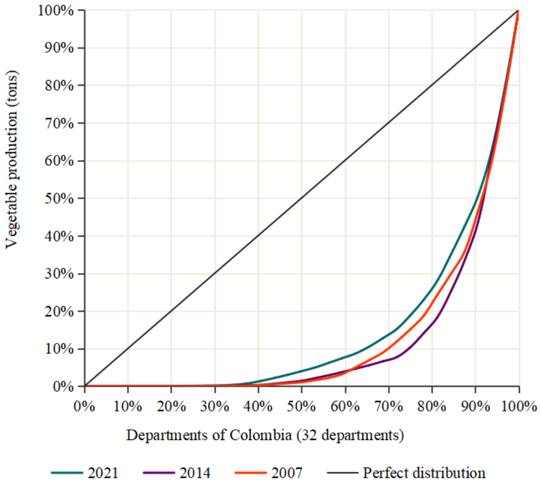
Source: Own elaboration based on data [5, 29].

Note: Watermelon*: Between 2006 and 2018 it is classified as a crop of the "Fruit group", not the "Vegetables group". Other vegetables** and Various vegetables*: this classification category is not specified in the Minagricultura-UPRA [5] database.

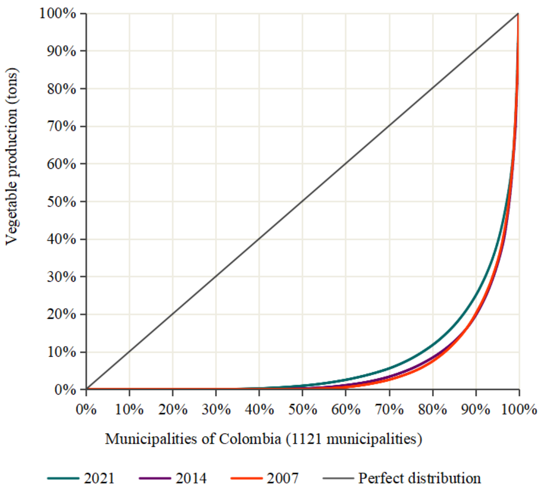
In contrast, when measured at the municipal level, we find that the concentration is much greater, reaching a Gini coefficient of 0.8836 in 2007, 0.8809 in 2014 and 0.8501 for 2021 (see **Figure 5b**), but with a variation of −3.8% between 2007 and 2021. This is paradoxical because although the regional concentration is almost constant over time, a reduction in municipal concentration can be observed, which can be explained by the fact that each year the number of municipalities that register production is more significant, indicating that within the productive regions there are municipalities that recently began to introduce vegetable crops as part of their agricultural productive structure. It can be said that in 2021, 16.6% of the Colombian municipalities are responsible for 85.0% of vegetable production.

3.3. Specialization of Vegetable Production in Colombian Municipalities

Of the 796 vegetable producing municipalities in the country in 2021 (see **Figures 6** and **7**), 50.0% equivalent to 398 municipalities have LQ greater than 1.0, only 24 municipalities (3.0%) have LQ equal to 1.0 and the remaining 374 municipalities that represent 47.0% have values lower than 0.99. The LQ values in the 374 municipalities that are representative oscillate between 1.11 and 27.02, being possible to identify that 83.4% of the frequencies fluctuate between 1.11 and 11. The 5 municipalities with the highest LQ values were Sáchica (27.02), Aquitania (25.53), Villa de Leyva (25.47), Guarne (25.17) and Marinilla (25.0). Comparatively, the 5 municipalities with the highest vegetable production in 2021 reached the following LQ values: Aquitania (25.53), Peñol (21.9), San Martín (13.8), Villa de Leyva (25.47) and Tona (24.2).



(**a**)



(**b**)

Figure 5. Lorenz Curve for vegetable production, by department (**a**) and by municipality (**b**): 2007, 2014 and 2021.

Source: Own elaboration based on data [5, 29].

Although production, agronomic yields (t ha^{-1}) and LQ should have a strong spatial correlation, only 96 municipalities overlap production and yields above 3,404.8 tons and 21.3 t ha^{-1} respectively, which were the national average in 2021. Within this group, 9 municipalities stand out for achieving production and yields of more 20,000 tons and 30 t ha^{-1}: Aquitania, Villa de Leyva, Sutamarchán and Toca in the department of Boyacá; Peñol, Marinilla, Santuario and Sonsón in the department of Antioquia; and Tona in the department of Santander.

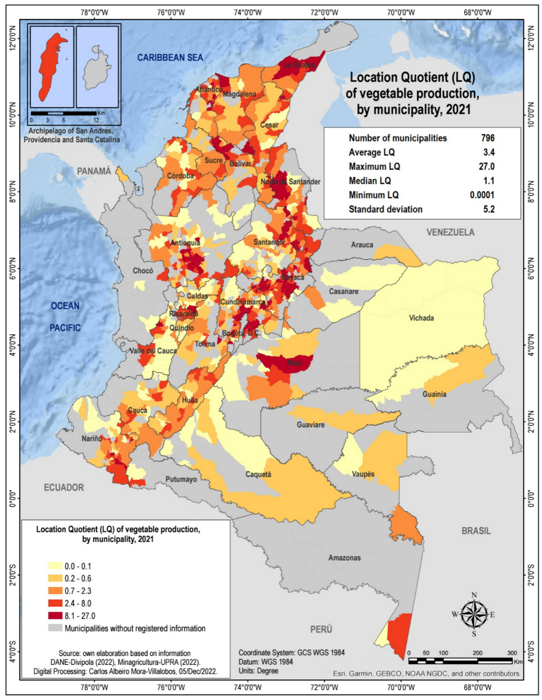


Figure 6. Location Quotient (LQ) of vegetable production, by municipality, 2021.

Source: Own elaboration based on data [5, 27].

Note: Intervals use Geometrical Interval methodology, ArcGIS version 10.7. In 2021, measurements of planted area, harvested area and agricultural production in Colombia were made using a methodology that included 8 crop groups.

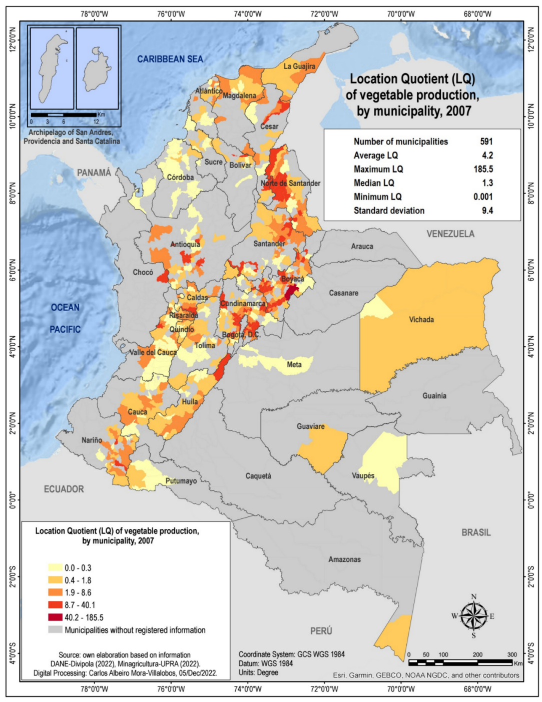


Figure 7. Location Quotient (LQ) of vegetable production, by municipality, 2007.

Source: Own elaboration based on data [5, 27].

Note: Intervals use Geometrical Interval methodology, ArcGIS version 10.7. In 2007, measurements of planted area, harvested area and agricultural production in Colombia were made using a methodology that included 12 groups crop.

3.4. Herfindahl-Hirschman Index (HHI), 2021

This study focused attention exclusively on vegetable cultivation; therefore, in this section, the specialization should be understood as the preference of farmers in a certain municipality to cultivated vegetables. For this reason, we extracted the section corresponding to vegetables cultivation from the calculation of the municipal HHI to observe which municipalities have specialization exclusively in vegetables cultivation.

In first place, among the 796 vegetable-producing municipalities registered in 2021, an average HHI index for vegetable crops of 0.021 is observed with a maximum value of 1.000 and a minimum of 0.000000001 (see **Figure 8**). To make a classification by quintile, we made a hierarchical scale with 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). We found only one municipality (0.1%) with very high specialization, 4 municipalities (0.5%) with high specialization, 4 municipalities (0.5%) with medium specialization, 12 municipalities (1.5%) with low specialization, and 775 municipalities (97.4%) with very low specialization. The only municipality with very high specialization in vegetable cultivation was Sáchica (Boyacá) (1.000); in addition, the municipalities with high and medium HHI were Aquitania (0.650), Tibasosa (0.605), Cuítiva (0.433) and Villa de Leyva (0.585) in Boyacá; Cajicá (0.771), Cota (0.619) and Mosquera (0.579) in Cundinamarca; and Tona (0.466) in the department of Santander.

For its part, in 2007 there were 592 municipalities with vegetable crops, of which only one municipality (0.2%) had very high specialization; no municipality was found with high specialization; 4 (0.7%) municipalities had medium specialization; 9 (1.5%) had low specialization; and 578 municipalities (97.6%) had very low specialization (see **Figure 9**).

On the other hand, between 2021 and 2007, a variation of 34.5% is observed in the number of municipalities that have an area cultivated with vegetables, equivalent to 204 new municipalities in 2021 that did not have cultivation in 2007. The area planted at the national level shows a variation of 20.4% between 2007 and 2021, the same does occur with the area planted with vegetables, which increased 75.6% from 72,188,0 hectares in 2007 to 126,809,9 in 2021. Additionally, the HHI calculation allowed us to find that between 2007 and 2021.

Figure 8 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 group. HHIvegetable_2021 indicates whether or not the municipality has specialization in vegetable cultivation. When the intercepts of the two variables, (HHImunicipality_2021 and HHIvegetable_2021), are found, it is identified that it is a municipality that has revealed specialization in the vegetable "crop group".

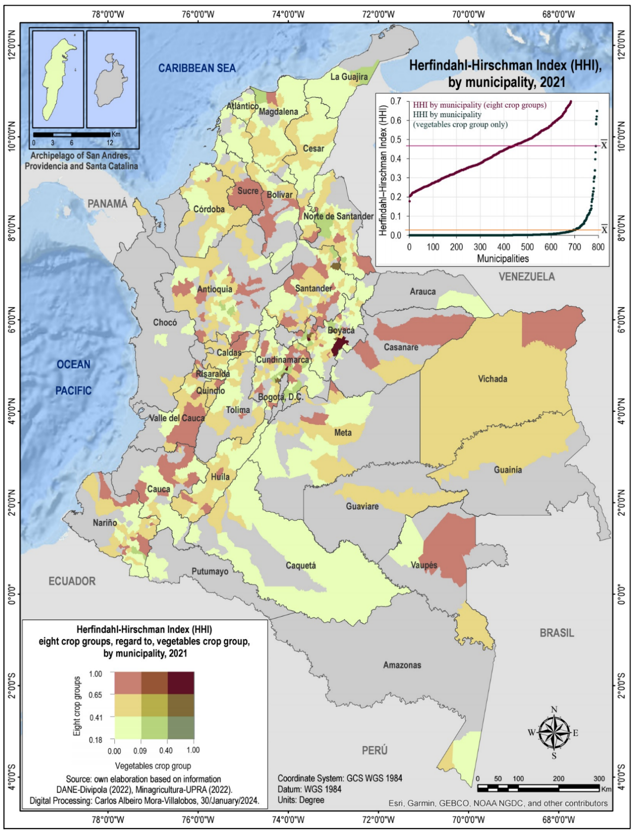


Figure 8. Herfindahl-Hirschman Index, crop groups and vegetable crops (planted area), by municipality, 2021.

Source: Own elaboration based on data [5, 27].

Note: Intervals use Natural Breaks (Jenks) methodology, ArcGIS version 10.7. In 2021, measurements of planted area, harvested area and agricultural production in Colombia were made using a methodology that included 8 crop groups.

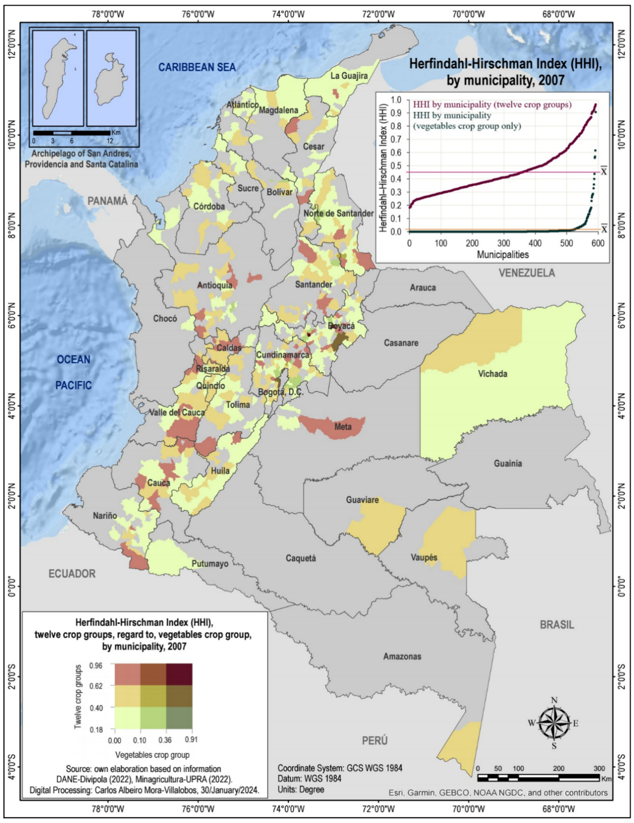


Figure 9. Herfindahl-Hirschman Index, crop groups and vegetable crops (planted area), by municipality, 2007.

Source: Own elaboration based on data [5, 27].
Note: Intervals use Natural Breaks (Jenks) methodology, ArcGIS version 10.7. In 2007, measurements of planted area, harvested area and agricultural production in Colombia were made using a methodology that included 12 crop groups.

3.5. Spatial Autocorrelation (Moran's I), 2021

According to 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 9.352235 which represents the standard deviation, the null hypothesis (H_0) that establishes that the values of the entities (polygons in the map) are randomly distributed is rejected, and it is identified that there is a probability of less than 1% that this grouping pattern could be the result of chance. Therefore, it is validated that in 2021 the production of vegetables in Colombia at the municipal level yields a Moran's I of 0.023962, which allows for establishing an agglomeration of the variable in groups of municipalities where there is a correlation of spatial contiguity that identifies a cluster structure [36].

Additionally, it is possible to find three types of productive agglomerations of vegetables: 1) high productive agglomeration located in Antioquia, Meta (Puerto López and the Ariari sub-region), southern Nariño, Boyacá, Antioquia, Bogotá (Sabana occidente), southern Cesar and Norte de Santander in the municipalities of San Calixto, Hacarí and La Playa; 2) medium productive agglomeration located in the departments of Huila, Cauca, Atlántico and Córdoba; and 3) low productive agglomeration distributed in municipalities of the departments of Antioquia, Boyacá, Santander, Meta, Casanare, Arauca and Vichada (see **Figure 10**).

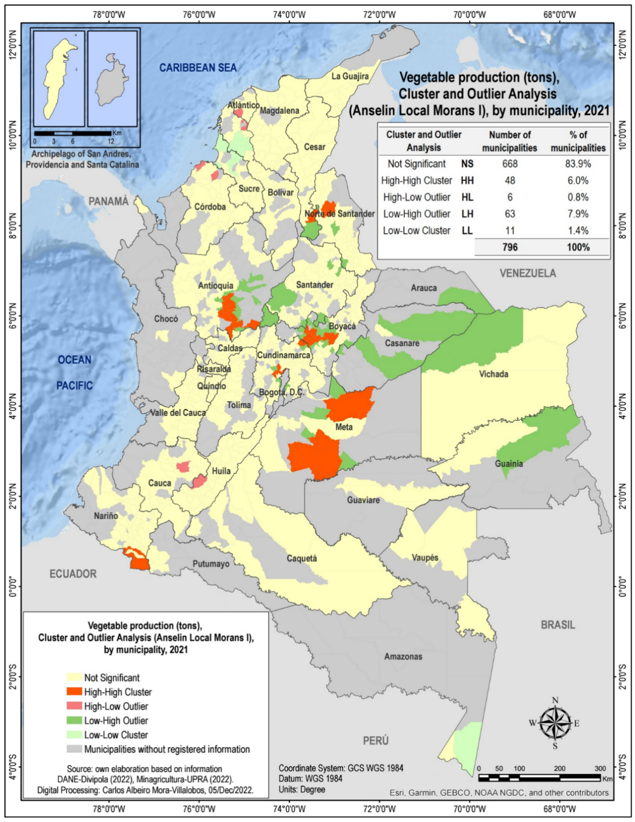


Figure 10. Cluster and Outlier Analysis (Anselin Local Morans I), vegetable production, municipalities, 2021.

Source: Own elaboration based on data [5, 27].

3.6. Sensitivity Analysis of Vegetable Crops to Changes in Temperature and Precipitation

According to Minagricultura-UPRA [5], in 2021 there were five (5) crops that concentrated 72.6% of the national vegetable production: tomato (31.4%), green onion (12.6%), carrot (10.2%), bulb onion (9.9%) and watermelon (8.6%) (see **Table 3**). Applying the OLS for each of these crops according to the specifications of the methodology—numeral 5, the following results are obtained:

- **Table 4** shows that tomato production has a positive association with AAT and an inverse association with TAP. These results indicate that for each additional unit in ATT, production will increase by 4,984.25 units; while for each additional unit in TAP there will be a reduction of 5.49 units in production. This reflects that excess rainfall is detrimental to tomato production. This reflects that excess rainfall is detrimental to tomato production. The relationship between the variables is statistically significant with a confidence interval (CI) of 95%.
- **Table 5** shows that onion production has a positive association with AAT and an inverse association with TAP. The results indicate that for each additional unit in AAT, onion production will increase by 28,377.99 units, suggesting that higher temperatures favor production. On the other hand, the TAP coefficient is negative, showing a reduction of 5.13 units in production for each additional unit of precipitation; this effect is not statistically significant, implying that rainfall does not clearly influence onion production. The relationship between AAT and production is statistically significant with a 95% confidence interval, while TAP does not show a conclusive effect in this context.
- The relationship between climatic variables (temperature and rainfall) and carrot, bulb onion, and watermelon production is not statistically significant in the OLS analyzed (see **Tables 6**, **7** and **8**). This suggests that climatic factors, as measured in this study, do not conclusively explain variability in the production of these crops. It is likely to require more data in the panel, the use of monthly rather than annual measurements, and the introduction of additional control variables to obtain more robust estimators that improve the precision of the analysis.

Although OLS does not explain a large part of the variability in production (R-sq overall low, e.g., 0.10% in the case of carrots), the fixed effects of municipalities are highly significant. This indicates that differences between municipalities, such as geographical features or local agricultural practices, play a key role in explaining variability in agricultural production. Therefore, it is likely that other factors not included in this OLS (such as access to agricultural inputs, soil quality, or local policies), are critical to better understanding the production of the crops studied in this sample.

Table 4. OLS for tomato production (t), AAT and ATP between 2007 and 2021.

Fixed-effects (within) regression				Number of obs	=	**255**
Group variable: **Municipali∼e**				Number of groups	=	**17**
R-sq:				Obs per group:		
within	=	**0.0671**		min	=	**15**
between	=	**0.0063**		avg	=	**15.0**
overall	=	**0.0094**		max	=	**15**
				F (**2, 236**)	=	**8.49**
corr (u_i, Xb)	=	**−0.6729**		Prob > F	=	**0.0003**

AreaCAFE	Coef.	Std. Err.	t	P > | t |	[95% Conf.	Interval]
AAT	**4984.25**	**2227.176**	**2.24**	**0.026**	**596.564**	**9371.935**
TAP	**−5.491806**	**2.401697**	**−2.29**	**0.023**	**−10.2233**	**−0.7603023**
_cons	**−72717.59**	**44411.75**	**−1.64**	**0.103**	**−160212**	**14776.53**
sigma_u	**19779.157**					
sigma_e	**13082.366**					
rho	**0.69566242**	(fraction of variance due to u_i)				
F test that all u_i = 0: F (**16, 236**) = **18.43**						Prob > F = **0.0000**

Source: Own elaboration based on data [5, 29, 30].

Table 5. OLS for green onion production (t), AAT and ATP between 2007 and 2021.

Fixed-effects (within) regression				Number of obs	=	**45**
Group variable: **Municipali∼e**				Number of groups	=	**3**
R-sq:				Obs per group:		
within	=	**0.2739**		min	=	**15**
between	=	**0.0226**		avg	=	**15.0**
overall	=	**0.0125**		max	=	**15**
				F (**2, 40**)	=	**7.54**
corr (u_i, Xb)	=	**−0.9306**		Prob > F	=	**0.0017**

AreaCAFE	Coef.	Std. Err.	t	P > | t |	[95% Conf.	Interval]
AAT	**28377.99**	**7323.124**	**3.88**	**0.000**	**13577.41**	**43178.58**
TAP	**−5.129578**	**16.45123**	**−0.31**	**0.757**	**−38.37876**	**28.1196**
_cons	**−339857.1**	**102845.9**	**−3.30**	**0.002**	**−547716.4**	**−131997.8**
sigma_u	**131545.74**					
sigma_e	**16658.254**					
rho	**0.98421676**	(fraction of variance due to u_i)				
F test that all u_i = 0: F (**2, 40**) = **122.89**						Prob > F = **0.0000**

Source: Own elaboration based on data [5, 29, 30].

Table 6. OLS for carrot production (t), AAT and ATP between 2007 and 2021.

Fixed-effects (within) regression				Number of obs	=	**105**
Group variable: **Municipali∼e**				Number of groups	=	**7**
R-sq:				Obs per group:		
within	=	**0.0104**		min	=	**15**
between	=	**0.0143**		avg	=	**15.0**
overall	=	**0.0010**		max	=	**15**
				F (**2, 96**)	=	**0.50**
corr (u_i, Xb)	=	**−0.1686**		Prob > F	=	**0.6054**

AreaCAFE	Coef.	Std. Err.	t	P> | t |	[95% Conf.	Interval]
AAT	**455.7923**	**1089.847**	**0.42**	**0.677**	**−1707.537**	2619.122
TAP	**−1.877316**	**2.297806**	**−0.82**	**0.416**	**−6.438425**	**2.683793**
_cons	**10384.48**	**17837.5**	**0.58**	**0.562**	**−25022.68**	**45791.63**
sigma_u	**10667.275**					
sigma_e	**8139.489**					
rho	**0.63202328**	(fraction of variance due to u_i)				
F test that all u_i = 0: F (**6, 96**) = **23.37**						Prob > F = **0.0000**

Source: Own elaboration based on data [5, 29, 30].

Table 7. OLS for bulb onion production (t), AAT and ATP between 2007 and 2021.

Fixed-effects (within) regression				Number of obs	=	**135**
Group variable: **Municipali∼e**				Number of groups	=	**9**
R-sq:				Obs per group:		
within	=	**0.0247**		min	=	**15**
between	=	**0.0017**		avg	=	**15.0**
overall	=	**0.0001**		max	=	**15**
				F (**2, 124**)	=	**1.57**
corr (u_i, Xb)	=	**−0.6298**		Prob > F	=	**0.2118**

AreaCAFE	Coef.	Std. Err.	t	P > | t |	[95% Conf.	Interval]
AAT	**−1890.542**	**1907.918**	**−0.99**	**0.324**	**−5666.85**	**1885.762**
TAP	**−4.974578**	**3.055778**	**−1.63**	**0.106**	**−11.0228**	**1.073662**
_cons	**49779.05**	**33054.43**	**1.51**	**0.135**	**−15644.9**	**115203**

Table 7. *Cont.*

sigma_u	**12193.431**	
sigma_e	**8952.3338**	
rho	**0.64975583**	(fraction of variance due to u_i)
F test that all u_i = 0: F (**8, 124**) = **15.78**		Prob > F = **0.0000**

Source: Own elaboration based on data [5, 29, 30].

Table 8. OLS for watermelon production (t), AAT and ATP between 2007 and 2021.

Fixed-effects (within) regression				Number of obs		=	**45**
Group variable: **Municipali∼e**				Number of groups		=	**3**
R-sq:				Obs per group:			
within	=	**0.0651**			min	=	**15**
between	=	**0.3787**			avg	=	**15.0**
overall	=	**0.1360**			max	=	**15**
				F (**2, 40**)		=	**1.39**
corr (u_i, Xb)	=	**−0.7520**		Prob > F		=	**0.2602**

AreaCAFE	Coef.	Std. Err.	t	P > | t |	[95% Conf.	Interval]
AAT	**11441.39**	**7007.812**	**1.63**	**0.110**	**−2721.928**	**25604.71**
TAP	**−0.8017336**	**5.980765**	**−0.13**	**0.894**	**−12.88931**	**11.28584**
_cons	**−282721.7**	**190873.3**	**−1.48**	**0.146**	**−668491**	**103047.7**
sigma_u	**37245.511**					
sigma_e	**19173.939**					
rho	**0.79050281**	(fraction of variance due to u_i)				
F test that all u_i = 0: F (**2, 40**) = **18.23**						Prob > F = **0.0000**

Source: Own elaboration based on data [5, 29, 30].

4. Discussion

This study used the Gini coefficient to observe the concentration of vegetable production, LQ and HHI to identify production specialization and the Moran index to establish agglomeration, being methodologies widely used for those purposes as shown in previous studies by Cosrojas and Eguia [38], Kartikawati, Sundari and Sundari [39], Castro and Fuentes [16], Schouten and Heijman [17], and Chasco Yrigoyen [40]. However, our analysis suggests that it is necessary to follow the behavior of prices and production because there could be a determining influence for the crop that is strongly correlated with the prices of the different vegetable crops and the increase in production volumes. In this regard, it is important to focus on the crops of watermelon, melon and pumpkin that have increased considerably in the departments of Meta, Sucre, Bolivar, Cordoba and Atlántico. Additionally, it could be that production costs, prices in wholesale supply centers and new trends in eating habits are positively influencing the growth of vegetable crops and the number of producing municipalities.

In this sense, for future studies on the agglomeration of vegetable production in Colombia, it would be ideal to analyze the implications of population growth in the departmental capital cities (which are the main market for the commercialization of vegetables), to identify if there is a correlation between the increase in vegetable production and consumption in a certain population segment, for example, the adult population over the age of 60. In addition, if vegetable production could be broken down by type of crop, specialized municipal clusters could be identified, which would lead to a detailed study of the value chains for the most economically important horticultural crops in the regions. This type of analysis would lead to identifying the economic impact of implementing innovation and technology in horticultural production in specific crops.

Since this study focused on the study of vegetable production to find the productive agglomeration (agricultural cluster), it is necessary for a next stage to analyze the value chain for tomato, bulb onion, green onion, carrot, lettuce, paprika, melon and watermelon, that is were identified as the crops with the highest production in Colombia. This study would make it possible to observe the behavior of business clusters, and thus contrast reality and theory in the framework of what FAO has defined as agro-based clusters (ABCs) [23].

It is important to emphasize that productive agglomeration requires decisive elements of the value chain to convert the comparative advantages derived from localized productive exploitation into competitive advantages, and thus create business clusters that increasingly respond to the figure of agro-industrial clusters (CAI) that include transformation processes oriented to value added, and not only centered on the idea of the agricultural cluster (CA). The main challenge for developing countries is transforming CAs into CAIs [25].

On the other hand, the findings of this work could positively affect agricultural policies and the economies of municipalities with vegetable production, through the following actions:

- Strengthen strategies that link the production of Peasant, Family and Community Agriculture (ACFC).
- Strengthen marketing channels using direct producer-consumer relationship mechanisms, e.g., short-circuit marketing.
- Promote vegetable crops to ensure food and nutritional security.
- Strengthen research in vertical agriculture and hydroponics.
- Implement organic and agroecological production techniques.
- Promote greater consumption in urban centers, especially leafy vegetables (lettuce, chard, spinach, cabbage, cauliflower, broccoli, parsley, celery, coriander, watercress, and green onions).
- Disseminate innovation and technology to improve production processes.
- Strengthen agricultural credit access programs in the municipalities where agricultural clusters have been identified.
- Promote the strategies of cooperatives and associations of small producers to access markets obtain better prices and standardize quality.
- Promote the strategic use of organic waste for compost production.
- Monitor and analyze the effects of climate change on the cost of production and the spread of vegetable pests and diseases.
- Analyze women's participation in vegetable production to improve gender equity relations and well-being in rural populations, among other topics.

It is important to note that a determining factor in this work was the lack of official statistical information on temperature and precipitation in several municipalities that are not close to departmental capitals, e.g., Puerto Lleras y San Martín (Meta), Majagual (Sucre), Cáqueza (Cundinamarca), Guarne y El Santuario (Antioquia), among others. In this regard, it is necessary to deepen the relationship between temperature variation and precipitation in the production of vegetable crops of economic and food importance for the country. Therefore, it would be relevant to replicate the OLS using panel data with monthly observations, in order to capture the seasonal effect in the months of higher heat and rainfall. Adicionalmente, se deben realizar experimentos de campo que fortalezcan los resultados obtenidos en este estudio. This would contribute to the design of public policies that would allow the development of strategies to adapt agriculture to climate change in municipalities where there is representative agricultural production.

5. Conclusions

The measurement of the departmental concentration of vegetable production showed a Gini coefficient of 0.7496 in 2007, 0.7674 in 2014 and 0.7072 in 2021, which leads to the conclusion that there have been no significant variations in regional concentration in last fifteen years. Likewise, it was established that at the municipal level there is a much higher concentration of production, although there is a slight decrease from a Gini of 0.8836 in 2007 to 0.8809 in 2014 and 0.8501 in 2021. This situation can be explained by the expansion of crops to municipalities where production was not previously recorded, for example, the subregion of Ariari in Meta; Yopal, Orocué and Paz de Ariporo in Casanare; the foothills of Caquetá; El Retorno in Guaviare; and the foothills of the Sierra Nevada de Santa Marta (Cesar, Magdalena and La Guajira).

The measurement of productive specialization found that vegetable production is strongly agglomerated in the central-eastern regions of the country, especially in the departments of Boyacá, Antioquia, Cundinamarca, Santander and Norte de Santander. By 2021, 398 municipalities are identified with LQ greater than 1.0, of which 66 are among the 20% of the highest values (between 12.03 and 27.02). Additionally, this study showed that in 2021, Colombia had 796 vegetable-producing municipalities, of which, 96 (12.1%) municipalities had production and yields higher than 3,404.8 tons and 21.3 t ha^{-1} (national averages). There were also 51 municipalities where vegetables accounted for more than 50% of agricultural production, the most representative being Sáchica (100%), Aquitania (94.5%), Villa de Leyva (94.3%), Guarne (93.2%) and Marinilla (92.6%). This situation is of particular interest due to the risks posed to these municipalities by climate change, the El Niño and La Niña phenomena, external economic shocks resulting from price fluctuations, and the possible proliferation of pests and diseases by changes in environmental temperature, especially in crops that are not planted in greenhouses.

On the other hand, the Moran index allowed us to identify that vegetable production at the municipal level tends to agglomeration, observing three types of clusters: 1) high agglomeration located in the departments of Antioquia, Meta, southern Nariño, Boyacá, Antioquia, Cundinamarca, southern Cesar and Norte de Santander; 2) medium agglomeration located over the departments of Huila, Cauca, Atlántico and Córdoba; and 3) low agglomeration distributed in municipalities of the departments of Antioquia, Boyacá, Santander, Meta, Casanare, Arauca and Vichada.

In closing, it is important to point out several aspects: 1) vegetable production shows a considerable increase that could be explained in consumer preference and the adoption of new food routines related to healthy diets that encourage the consumption of fruits and vegetables; 2) the most representative crops in the three time periods analyzed are tomato, green onion, bulb onion and carrot; 3) Colombia does not seem to have a revealed preference for leafy vegetables such as lettuce, chard and spinach; 4) judging by vegetable production figures in the years studied, domestic consumption shows a preference for condiment and salad vegetables (tomato, onion and carrot); 5) Antioquia, Cundinamarca and Boyacá are the departments with the highest production due to the comparative advantages of altitude, temperature and soil; however, the increase in the production of patilla (watermelon), melon and ahuyama in the departments of Meta, Sucre, Bolívar, Córdoba and Atlántico is noteworthy; 6) high vegetable production is identified in the municipalities of the *western savannah* of Bogotá, taking advantage of the particular advantage of having the main supply center of the country (Corporación de Abastos de Bogotá - Corabastos), as well as a potential market of 8 million inhabitants (16% of the national population).

Finally, it is important to highlight the need to continue studying vegetable production at the municipal level due to the economic importance for agricultural production in the territories, addressing other aspects related to the articulation of the value chain, the socioeconomic impacts of climate change, production in controlled hydroponic environments and vertical crops, the organic production, pest and disease management with biological control mechanisms and agroecological fertilizers, the contribution and connection of family farming in vegetable production chains, among other varied topics.

Author Contributions

Statistical analysis of data, elaboration of tables and figures, elaboration of thematic cartography, and writing of the paper, C.A.M.V.; Statistical analysis of data, writing of the paper, revision of the final paper, and approval of the manuscript for submission to RWAE.J.A.R.A.; Statistical analysis of data, elaboration of tables, writing of the paper, and statistical modeling in Stata, L.C.B.C.

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Data Availability Statement

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.

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Conflicts of interest

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

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