Coelho Junior *et al.*
Sustainable Environment Research (2024) 34:17
https://doi.org/10.1186/s42834-024-00223-z

Sustainable Environment Research

RESEARCH

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Supply of bioelectricity from sugarcane bagasse in Brazil: a space–time analysis

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Abstract

Bioelectricity generation from sugarcane is significant across Brazil and is related to regional market structure characteristics where the mills are located. To understand the distribution and conjuncture of this sector, this study analyzes the pattern of location, concentration and clustering of the bioelectricity supply from sugarcane bagasse in Brazil, for 2017 and 2022. The data were obtained from the Brazilian National Electric Energy Agency, and the methodology was based on concentration indices and scan statistics. The results showed that the Southeast region presented the most thermoelectric power plants and installed capacity. The Southeast and Midwest regions were highly concentrated in terms of quantity and sugarcane bioelectricity installed capacity. Five clusters were identified for the number of power plants in 2017; for 2022, there were eight clusters. Regarding installed potential, there were 14 clusters in 2017 and 23 clusters in 2022, all statistically significant. The existence of clusters provides information on the competitive advantages in the national market, which can drive new investments in more densified areas or in the neighborhood. Identification of the location and concentration pattern showed that facilities in the state of São Paulo and the Northeast coast were responsible for the most important share of supply. These results indicate to investors the impact of electricity generation on the sector and the most relevant location for installing new thermoelectric plants.

Keywords Bioenergy, Green energy, Regional economics, Energy security

1 Introduction

Brazil is one of the world's leading sugarcane producers, with increased production in recent years due to bioenergy demands [1]. Brazil is the leading producer of sugarcane ethanol and the pioneer in using ethanol as vehicle fuel – most of its ethanol production is domestically consumed as ethanol fuel or added to gasoline [2]. Brazilian ethanol is mainly produced from sugarcane, which is employed to produce sugar and first-generation ethanol. Sugarcane ethanol is technically and economically more efficient than ethanol from other crops, with 45% more ethanol produced per unit of land than ethanol from corn, the world's most widely used feedstock [3]. Furthermore, second-generation ethanol, produced

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from sugarcane waste (straw and bagasse), has shown increased production [4].

Sugarcane bagasse has high fiber content and, as a result, another prominent activity for this chain is its use in producing steam and electricity in the sugar and ethanol industry [5]. Besides meeting industrial energy demands, sugarcane bagasse can generate surplus electricity exported to the Brazilian electric grid. Sugarcane bagasse bioelectricity can be very relevant to Brazil, relieving the national electric system during low precipitation periods (low levels of hydroelectric reservoirs) [6]. In 2022, electricity production from sugarcane bagasse was 32.26 TWh (4.76% of the Brazilian electricity mix), of which 57.31% was injected into the grid (National Interconnected System) [7].

Sugarcane bagasse bioelectricity can be financially viable [8, 9] and presents the potential to mitigate climate change due to avoided emissions [10]. Fossil fuels have a higher energy density than biomass. For example, hard coal produces an average of 1.96 MWh t^{-1} of fuel, but its greenhouse gas (GHG) emissions are significantly high at 820 g CO_2 kWh^{-1} [11]. A traditional sugar mill produces an average of 7,740 MJ of specific calorific energy and 30 kWh of electricity t^{-1} of sugar cane processed, while other biomass sources that are important contributors to electricity generation in Brazil, such as black liquor and forest residues, provide 90 and 4.4 kWh kWh t^{-1}, respectively [12–14]. Emissions can be avoided by capturing and storing the carbon dioxide released during fermentation, which has already been studied in Brazil [15]. The use of sugarcane bagasse to generate bioelectricity and produce fuels is part of the Brazilian strategy to reduce carbon emissions, falling under its *Intended Nationally Determined Contribution* and also contributing to the management of residues [16].

Lopes Silva et al. [17] verified that 92.1% of the GHG emissions associated with bioelectricity production were associated with the harvesting process (primarily due to the burning of straw before harvesting and transportation). Carvalho et al. [18] confirmed that producing electricity from sugarcane bagasse presented a low carbon footprint, and when diesel-based electricity was displaced by bioelectricity, overall avoided emissions of 0.833 kg CO_2-eq kWh^{-1} were achieved.

Although significant throughout the Brazilian territory, the generation of bioelectricity from sugarcane is associated with regional market structures. According to Cardoso et al. [19], Brazil's processing capabilities and configurations of sugarcane industrial facilities are based on regional averages and are site-dependent. Industrial concentration studies are based on the need to understand market structures and are relevant to evaluating the competitiveness of organizations. Industrial economics helps understand the interactions and real dynamics of industries [20]. Authors such as Hall and Hall and Hitch [21], Mason [22], and Coase [23] contributed to the development of organizational assessments in imperfect market structures. Based on Mason [22] and Bain [24] economic development and market structure, start from the concentration level between participants or barriers to the entrance of participants. According to Devine et al. [25], four basic dimensions of market structure are seller concentration, buyer concentration, product differentiation, and entry barriers. Industrial economics studies are associated with variables such as the amount and size of organizations and are influenced by the behavior of the competition [26]. There has been recent widespread attention to rising industrial concentration and market power in the U.S. economy, leading to major macroeconomic trends such as increasing corporate profits, slowing investments, declining labor share of income, and growing income and wealth inequalities [27].

In the same sense, scan statistics is an instrument of spatial economics that identifies conglomerates [28] and is a leading tool for the successful analysis of geographical and spatial data, with applications in epidemiology, disease surveillance, crime prevention, and environmental sciences [29]. Organizations or firms of a specific segment can be grouped in a geographic zone, forming spatial clusters. From the early industrial studies of the nineteenth century, Marshall [30] brought the concept of "external" economy that incorporates advantages to industrial conglomerates. Industrial clusters can promote competitiveness by increasing the productivity of the companies within the clusters, driving innovation, and stimulating new businesses in the specific field [31].

Using the notion of special clusters, a research was conducted by Coelho Junior and Santos Junior [32] regarding the concentration of forest biolectricity in Brazil as to understand market dynamics. The authors concluded that the spatial–temporal effect (observed with scan statistics) revealed that the Brazilian forestry bioelectricity conglomerates are located in the Midwest-South region. This type of assessment is crucial to identify the offer of forestry bioelectricity and the thermoelectric power plants that use cogeneration. In a more recent research, Coelho Junior et al. [33] analyzed the concentration and spatial distribution of the black liquor thermoelectric plants in Brazil. The aim was to support viability studies on the implementation of energy enterprises. There is a clear contribution to the decision-making process on the location of future facilities, diversification of the national electricity matrix, and increase of energy security and efficiency in the country. When analyzing industrial concentration, its identification is frequently based on geographic concentration and industrial-specific indices

[34]. Despite the importance of sugarcane bagasse bioelectricity, no studies were found on the allocation of productive resources (e.g., funding, specialized labor), which could lead to higher productive efficiency, sustainable local development, and generate jobs and income [35].

Recognizing the lack of studies on the spatial distribution of sugarcane bagasse bioelectricity in Brazil and its importance to the Brazilian energy matrix, this study analyzes the pattern of location, concentration, and clusters of bioelectricity supply from sugarcane bagasse in Brazil. Exploring bioelectricity supply in Brazil can help unravel the market structure of sugarcane bagasse distributed generation and the dynamics of using this resource for 2017 and 2022.

2 Material and methods

2.1 Database

Information on Brazilian thermoelectric plants, from 2000 to 2019, is available at the Generation Information System (SIGA) of the Brazilian National Electric Energy Agency (ANEEL) [36, 37]. The thermoelectric plants that use sugarcane bagasse in Brazil (Fig. 1) [38] are classified as level 1 (agro-industrial biomass) and then as level 2 (which encompasses the use of sugarcane bagasse, agro-industrial biogas, elephant grass, and rice husks). For each thermoelectric plant identified, the installed power (in MW) and geographical coordinates were collected. Figure 1 shows the location of South America, Brazil (by region), and the distribution of sugarcane bagasse thermoelectric plants in 2022.

These plants were spatialized with QGIS 3.6.0®, using geographical coordinates. A conjuncture analysis was carried out considering the Brazilian regions and federal units to visualize the dynamics of the power plants and the power granted (MW) for 2017 and 2022. The Geometric Growth Rate (GGR) was used to estimate the annual gains and losses of forest-based thermoelectric plants, according to Eq. (1)

$$RGG[\%] = [(V_F/V_O)^{1/\Delta t} - 1] * 100 \tag{1}$$

in which V_F is the amount or power granted (MW) of sugarcane bagasse biomass in the final year; V_0 represents the quantity or power of the initial year; and Δt is the temporal variation (expressed in years).

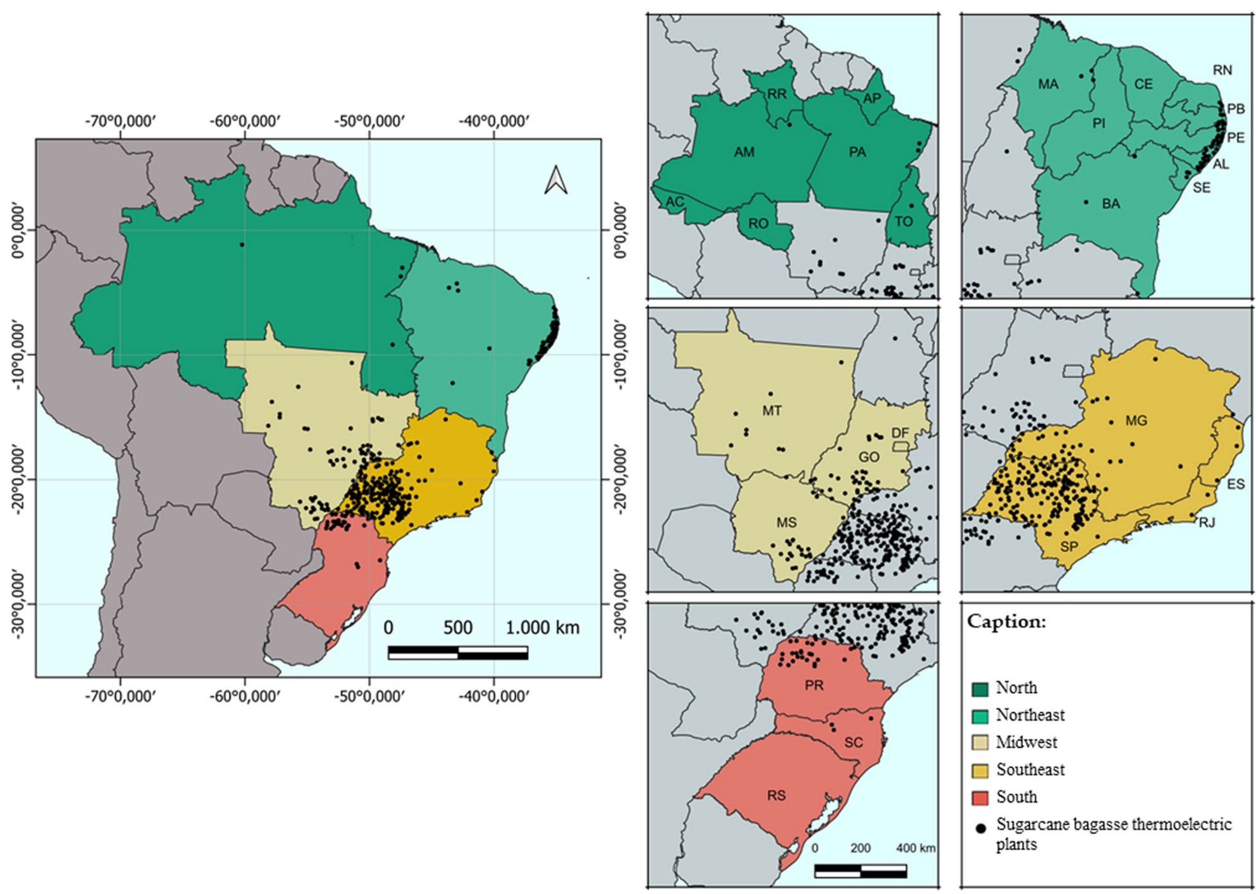

Fig. 1 Spatial distribution of sugarcane bagasse power plants in Brazilian regions and states in 2022. Source: IBGE [38]

2.2 Measures of location, concentration, and inequality

The location, concentration, and inequality measures used were: Location Quotient (LQ), Concentration Ratio [CR(k)], Adjusted Herfindahl–Hirschman Index (HHI'), and Gini coefficient (Gi). Concentration indices assist in the diagnosis and understanding of a given market, which can be classified as partial and summary [39]. The indicators used were (Table 1): LQ, CR(k), HHI', and Gi. It evaluated sugarcane bagasse thermoelectric plants and their power output in the Brazilian states and the energy supply of these plants.

The LQ relates the relative share of the productive segment due to this activity to a reference region. The LQ was used to identify the specialized federal units regarding the number of thermoelectric plants and the power granted for sugarcane bagasse for 2017 and 2022. The LQ can be classified as: unspecialized (LQ < 0.5), weak specialization (0.5 ≤ LQ < 1), productive distribution (1 ≤ LQ < 3), and productive specialization (LQ ≥ 3) [40].

The CR(k) is obtained from the descending order of the k (k = 1, 2, …, n) shares of states or companies. The concentrations of the four [CR(4)] and eight [CR(8)] largest states and companies were calculated and classified according to Bain [24] (Table 2).

The *HHI* analyzes the market structure based on the squared market share of states with thermoelectric plants (quantity or potential installed) or sugarcane bagasse companies. Resende [41] created the adjusted HHI (*HHI'*, varying between 0 and 1) to compare studies spanning different time intervals. For an atomized market $HHI' < 0.10$, for a non-concentrated market $0.10 \leq HHI' < 0.15$, for a moderately concentrated market $0.15 \leq HHI' < 0.25$, and for a concentrated market $HHI' \geq 0.25$.

The *Gi* measures social inequality based on population income [42]. Currently, the *Gi* has been applied in different areas of study and can be used to measure inequality in the supply of electricity from sugarcane bagasse. *Gi* can classify the inequalities as zero to weak ($0.00 \leq Gi < 0.250$), weak to medium ($0.25 \leq Gi < 0.500$), medium to strong ($0.501 \leq Gi < 0.700$), strong to very strong ($0.701 \leq Gi < 0.900$) and very strong to absolute ($0.900 \leq Gi \leq 1.000$) [42].

2.3 Scan statistics

Scan statistics used a purely spatial analysis for high conglomeration, based on the Poisson probabilistic model and the maximum likelihood method, for a region Z, divided into m sub-regions. The parameters were: the cluster candidate zone (z) in Brazil, and the probability of the sugarcane bagasse thermoelectric plant being inside (p) or outside (q) z. Equation (2) is the null hypothesis ($p = q$) of the likelihood function (L_0) [43].

$$L_0 = \frac{e^{-C}}{C!}\left(\frac{C}{N}\right)^{C}\prod_{j=1}^{m} n(j) \tag{2}$$

in which C = the installed power or number of sugarcane bagasse thermoelectric plants in Brazil, $C!$ = factorial value of the installed power or number of sugarcane bagasse thermoelectric plants, n = number of thermoelectric plants or total installed power, and $n(j)$ = number of thermoelectric plants or total installed power within each sub-region m. Equation (3) is the alternative hypothesis ($p > q$) given by the likelihood function [$L(z,p,q)$] [43].

$$L(z,p,q) = \frac{e^{[-pn(z)-q(N-n(z))]}}{C!}p^{C(z)}q^{C-C(z)}\prod_{j=1}^{m} n(j) \tag{3}$$

in which $n(z)$ = number of thermoelectric plants or total installed power in z, $C(z)$ = installed power or number of sugarcane bagasse thermoelectric plants in z. Equation (4) represents the likelihood ratio $LR(z)$.

$$LR(z) = \frac{L(z,p,q)}{L_0} = \begin{cases} \left(\frac{C(z)}{\mu(z)}\right)^{c(z)}\left(\frac{C-C(z)}{\mu(z)}\right)^{C-c(z)}, & se\ \frac{C(z)}{\mu(z)} > 1 \\ 1 & , otherwise \end{cases} \tag{4}$$

Table 1 Measures of location, concentration and inequality

Indices	Equation	Interval
Locational Quotient	$LQ = \frac{\frac{E_{ij}}{E_j}}{\frac{E_i}{E}}$	0 ≤ LQ
Concentration Ratio	$CR(k) = \sum_{i=1}^{k} Si$	0% ≤ $CR(k)$ ≤ 100%
Herfindahl–Hirschman Adjusted	$HHI\prime = \frac{1}{n-1}(n * HHI - 1);\ n > 1$	0 ≤ HHI' ≤ 1
Gini Index	$G = 1 - \frac{\left[\sum_{i=1}^{n}(Sij+Si)\right]}{n}$	0 ≤ G ≤ 1

E_{ij} Supplied power of sugarcane bagasse in state j, E_j Supplied power in state j, *Ei* Supplied power of sugarcane bagasse in Brazil and E = Supplied power in Brazil. S_i = participation sugarcane bagasse thermoelectric plants and states (based on supplied capacity, MW); i = State or thermoelectric of the observed sugarcane bagasse. n = number of participants, *Sij* Participation cumulative of sugarcane bagasse thermoelectric plants and states (based on supplied capacity, MW)

Table 2 Classification the Concentration Ratio indicator [CR(k)]

Concentration level	Four largest (%)	Eight largest (%)
Very High	$CR(4) \geq 75$	$CR(8) \geq 90$
Moderately High	$65 \leq CR(4) < 75$	$85 \leq CR(8) < 90$
Moderately High	$50 \leq CR(4) < 65$	$70 \leq CR(8) < 85$
Moderately Low	$35 \leq CR(4) < 50$	$45 \leq CR(8) < 70$
Low	$CR(4) < 35$	$CR(8) < 45$

Source: Bain [24]

Under the null hypothesis, μz = is the expected value of the installed power or number of sugarcane bagasse thermoelectric plants in z.

The logarithm was used ($log\ [LR(z)] = LLR(z)$) to stabilize the variance, and the circular windows were associated with the ratio between the number of sugarcane bagasse thermoelectric plants and all thermoelectric power plants (8.16% for 2017 and 3.12% for 2022) and the ratios regarding national installed capacity (6.75% for 2017 and 5.25% for 2022). The $LLR(z)$ results were compared via Monte Carlo simulations (9,999 replications), considering a significance level under 5% ($p\text{-}value < 0.05$) by Eq. (5) [28].

$$value\ p = \frac{Ranking}{(1 + \#replications)} \tag{5}$$

Ranking refers to the $LLR(z)$ ranking, and #replications refers to the number of replications. The relative risk (RR) of installed power or number of sugarcane bagasse being within a cluster [43] is given by Eq. (6).

$$RR = \frac{i/E[i]}{(C - i)/(E[C] - E[i]} \tag{6}$$

$E[C]$ = is the mathematical expectation of the quantity of sugarcane bagasse thermoelectric plants or power installed, i is the quantity of sugarcane bagasse thermoelectric plants or power installed within the cluster, and $E[i]$ = is the mathematical expectation of the amount of sugarcane bagasse thermoelectric plants or power installed within the cluster.

The characteristics of the clusters identified were evaluated using the centroid of the conglomerate, the radius R (km), the observed value (Obs.), the expected value (Esp.), the RR, the LLR, and the p-value.

3 Results and discussion

Table 3 shows the regional distribution of sugarcane bagasse thermoelectric plants and the installed capacity (MW) in Brazil in 2017 and 2022. The scenario analysis shows an average growth of 1.74% per annum (p.a.) for the number of sugarcane thermoelectric plants, accompanied by an increase of 2.91% p.a. for installed power.

In 2017, the Southeast region had the highest number of thermoelectric plants (62.00%) and installed potential (63.78%) in the country. The states of São Paulo and Minas Gerais (in the Southeast) produced around 35% of the country's sugarcane in the 2016/17 harvest, according to the Ministry of Agriculture, Livestock and Supply [44].

The Midwest presented the second-highest number of sugarcane bagasse thermoelectric plants and installed potential, with 15.75 and 23.51%, respectively. The Midwest experienced pronounced sugarcane expansion, with production growth rates for the states of Goiás, Mato Grosso and Mato Grosso do Sul among the four highest in Brazil [45]. The Northeast follows in third place, with 57 thermoelectric plants (14.25%) and 870.97 MW installed (7.81%), the South presented 30 plants (7.50%) with 540.22 MW installed (4.84%), and finally the North region ranks in fifth place, with only two thermoelectric plants and 6.25 MW installed.

For 2022, the distribution between regions was similar, with strong growth in the Southeast, which accounted for 61.93% of thermal plants and 63.55% of installed power. The other regions presented less pronounced growth. The Midwest remained the second largest region, with 16.74% of the power plants and 24.21% of the power.

At the state level, São Paulo presented the most thermoelectric plants and installed potential, with 50.25 and 51.36% respectively in 2017. There is a high number of sugarcane bagasse thermoelectric power plants installed in the interior of São Paulo. Rudorff et al. [46] and Ogura et al. [47] highlighted the expansion of the agricultural frontier for producing sugarcane for energy in São Paulo, especially in the northwest and west areas. For 2022, São Paulo remained the leader in the ranking, but its percentage share decreased due to growth in the states of Minas Gerais, Mato Grosso, and Goiás.

The state of Minas Gerais was the second-highest producer of bioelectricity, with 1,302.42 MW installed (11.67%) and 43 plants (10.75%) in 2017, and 1,596.92 MW (11.69%) and 51 plants (12.39%) in 2022. The states of Goiás, Paraná, and Mato Grosso do Sul followed in the number of power plants and installed capacity. Claros Garcia and Von Sperling [48] mentioned that these states present favorable climate for the production of sugarcane, which explains the high production rates. Sugarcane is one of the world's most important C_4 crops (corn, sorghum, sugarcane, millet, and switchgrass), with accelerated growth in tropical and subtropical regions due to water availability and temperature [49]. Even in the context of global climate change, production is expected to increase in São Paulo, Goiás, Paraná, and Mato Grosso do Sul [50]. Nevertheless, production in the northeastern states is expected to decline due to water shortages caused by increased temperatures [51].

Table 3 Regional distribution of sugarcane bagasse thermoelectric plants and installed capacity (MW) in Brazil, for 2017 and 2022

Regions / States	2017		2022	
	Amount	Installed power	Amount	Installed power
Southeast	**248**	**7116.82**	**270**	**8185.37**
São Paulo	201	5731.00	214	6470.25
Minas Gerais	43	1302.42	51	1596.92
Rio de Janeiro	1	44.00	2	49.00
Espírito Santo	3	39.40	3	69.20
Midwest	**63**	**2623.68**	**73**	**3118.11**
Goiás	32	1276.27	38	1565.62
Mato Grosso do Sul	22	1078.49	25	1271.57
Mato Grosso	8	188.93	9	200.93
Tocantins	1	80.00	1	80.00
Northeast	**57**	**870.97**	**58**	**961.52**
Alagoas	21	308.86	21	357.46
Pernambuco	20	315.11	20	310.45
Paraíba	5	98.10	5	101.50
Sergipe	5	59.70	5	59.70
Maranhão	2	9.40	2	9.40
Rio Grande do Norte	2	57.00	2	61.00
Bahia	1	14.00	2	38.50
Piauí	1	8.80	1	23.5
South	**30**	**540.22**	**32**	**598.31**
Paraná	27	529.15	29	587.24
Santa Catarina	3	11.07	3	11.07
North	**2**	**6.25**	**3**	**17.45**
Amazonas	1	5.00	1	5.00
Pará	1	1.25	2	12.45
Brazil	**400**	**11157.94**	**436**	**12880.76**

Source: ANEEL [36]

Figure 2 shows the LQ of sugarcane bagasse thermoelectric plants and the installed capacity (MW) in Brazil for 2017 and 2022.

In 2017, Alagoas and Mato Grosso do Sul presented the highest productions. The Alagoas unit, with an LQ of 5.37, was the most specialized region and stood out as the main supplier of sugarcane bioelectricity in northeastern Brazil. Santos Junior et al. [52] identified a potential of up to 2.29 Mt of oil equivalent for sugarcane products in Alagoas, making it the most prominent exponent of this resource in the Northeast region. Mato Grosso do Sul presented an LQ of 3.41 for the number of thermoelectric plants. This was due to the low number of generators, only 79 units. As a result, 31.64% of the thermoelectric plants were powered by sugarcane bagasse. Other states with a strong influence of sugarcane bagasse bioelectricity were Goiás, São Paulo, Paraíba, Pernambuco, Paraná, and Sergipe, all with productive distribution.

For 2022, the main change was in the productive specialization of Goiás, São Paulo, Paraná, Sergipe, and Pernambuco, all of which were in the productive distribution category in 2017. The main reason for this increase in specialization was the installation of many photovoltaic solar and wind systems in the North-Northeast region [53].

For installed power, in 2017, the states of Alagoas (LQ = 5.95), Mato Grosso do Sul (LQ = 5.74), and São Paulo (LQ = 3.49) demonstrated productive specialization. For 2022, only Alagoas, São Paulo, and Goiás presented the maximum level of specialization. Mato Grosso do Sul began to exhibit weak specialization due to the expansion of installed power from forest biomass, especially from black liquor [33]. Only the state of Minas Gerais was in the productive distribution class, with LQ 1.01. The non-specialized states were mainly located in the country's North and Northeast, with only Alagoas, Pernambuco, and Paraíba not in this class.

An analysis was also carried out to assess the supply structure on the concentration indices of the quantity and installed potential (MW) of sugarcane bagasse

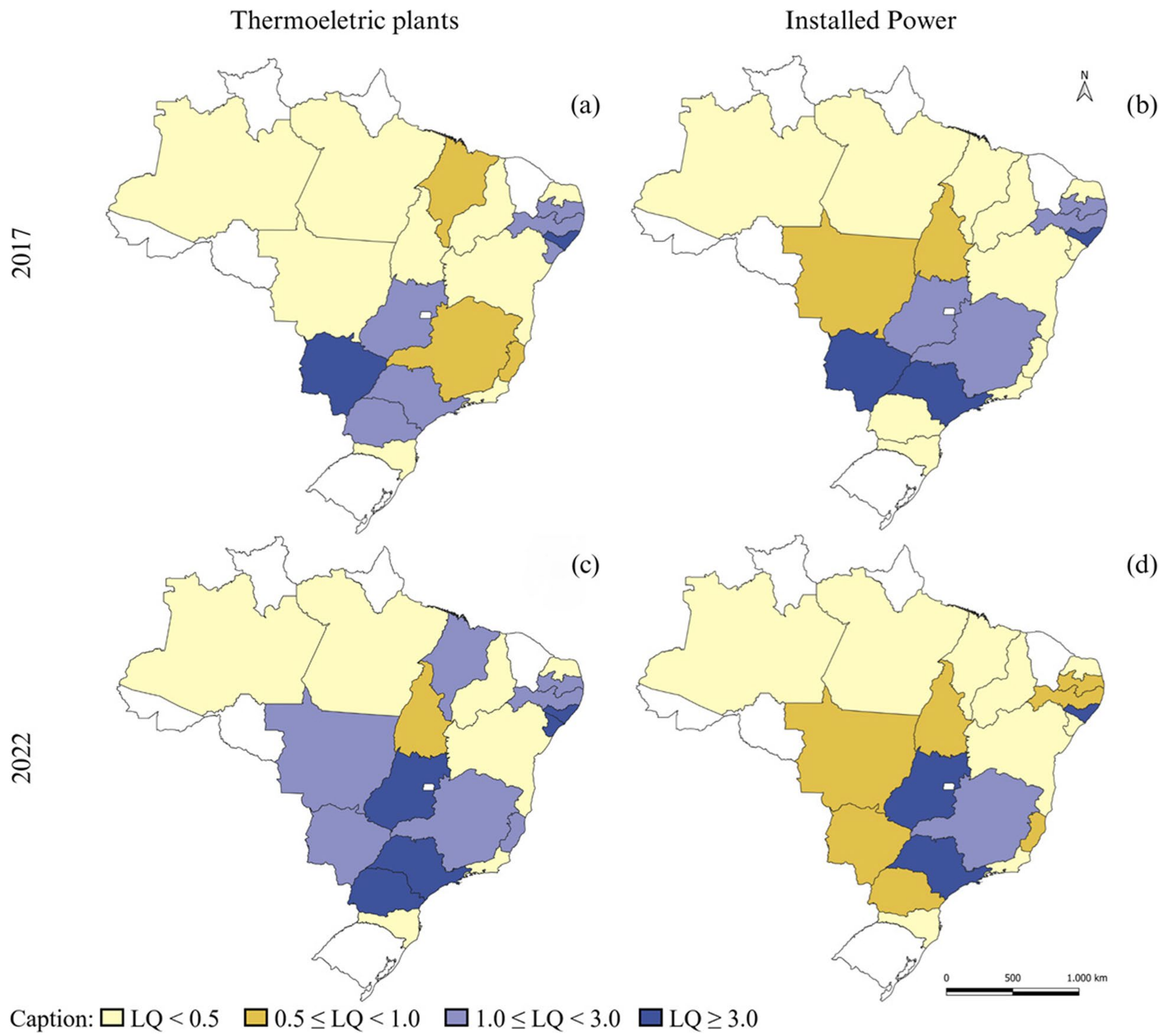

Fig. 2 Locational coefficient of sugarcane bagasse thermoelectric plants and installed capacity (MW) in Brazil, for 2017 and 2022

thermoelectric plants for the Brazilian states in 2017 and 2022 (Table 4).

For the number of thermoelectric plants, the state of São Paulo was in *CR*(*1*) for 2017 and 2022, with 50.25 and 49.08%, respectively. The state of Minas Gerais was added to *CR*(*2*) with 61.00% (in 2017) and 60.78% (in 2022). Analysis of *CR*(*4*) characterized the distribution of sugarcane bagasse thermoelectric plants as very high concentration [24]. The four most contributing states were São Paulo, Minas Gerais, Goiás, and Paraná, totaling 75.75% (in 2017) and 76.15% (in 2022). *CR*(*8*) also indicated a high degree of concentration for supply, with 93.50% (in 2017) and 93.34% (in 2022). In addition to the states participating in *CR*(*4*), Mato Grosso do Sul, Alagoas, Pernambuco, and Mato Grosso were also part of *CR*(*8*).

For the *HHI'* summary index, the distribution of thermoelectric plants was classified as moderately concentrated for 2017 and 2022. Although there is a clear dominance of the state of São Paulo, the small number of market participants ($n = 20$) tends to soften the effect of concentration [54]. For the Gi, the number of thermoelectric plants was classified as presenting strong to very strong inequality.

For installed power, the concentration between the states was similar. São Paulo was the leading supplier state with *CR*(*1*) = 51.36% (in 2017) and 50.23% (in 2022). For *CR*(*4*), Mato Grosso do Sul (instead of Paraná) was the fourth state with the most installed power, and the supply was highly concentrated. For *CR*(*8*), the classification was also as "highly concentrated". For *HHI'* the

Table 4 Concentration of Brazilian states and sugarcane bagasse thermoelectric plants (quantity and installed capacity—MW) in Brazil, for 2017 and 2022

	2017			2022		
	State		Power plants	State		Power plants
	Quantity	Installed Power		Quantity	Installed Power	
CR(4)	75.75%	84.14%	5.09%	76.15%	84.65%	4.33%
CR(8)	93.50%	96.17%	9.52%	93.34%	95.96%	8.09%
HHI'	0.25	0.27	0.003	0.24	0.26	0.002
Gi	0.79	0.82	0.77	0.79	0.81	0.75
n	20		400	20		436

CR (k) Concentration Ratio, *HHI'* Adjusted Herfindahl–Hirschman Index, *Gi* Gini Index, *n* Number of participants

power supply was characterized as concentrated. *G* indicated a strong to very strong concentration.

Market characteristics were also assessed among sugarcane bioelectricity supply agents. For 2017, *CR*(*1*) had a share of 1.43% for Porto das Águas (160 MW), located in Chapadão do Céu (Goiás state). In 2022, the thermoelectric plant with the most power available was Cerona (150 MW), in Nova Andradina (Mato Grosso do Sul) – this occurred because the power of Porto das Águas was split into two units. The ElDorado thermoelectric plant, in Rio Brilhante (Mato Grosso do Sul), was added to *CR*(*2*) in 2017 and 2022.

CR(*4*) showed a value of 5.09%, with the addition of the Barra Bioenergia (São Paulo) and Cocal II (SP) thermoelectric plants. The classification was “low concentration” for 2017 and 2022. Regarding the *CR*(*8*) of 9.52% (in 2017) and 8.09% (in 2022), the offer was classified as low concentration. The *HHI'* contributed to the analysis by attributing the characteristics of an atomized market. Only the *Gi* index displayed an opposite result, inferring a strong to very strong inequality.

Figure 3 shows the clusters of the amount (Fig. 3a and c) and installed potential (Fig. 3b and d) of sugarcane bagasse thermoelectric plants in Brazil, in 2017 and 2022. In 2017, the clusters of thermoelectric power plants were located in the Midwest region, in some parts of the northeastern coast, and the interior of the states of São Paulo and Minas Gerais. The western region of São Paulo presented many facilities due to the existing infrastructure for transporting sugar and alcohol production, which attracts the installation of sugarcane mills [55].

Regarding installed potential, several clusters only showed an increase in radius compared to the number of thermoelectric plants, with those in the Midwest region and the western part of the states of São Paulo and Minas Gerais remaining the same. A cluster emerged involving the states of Espírito Santo, Rio de Janeiro, and portions of Minas Gerais, São Paulo, and Bahia.

For 2022, there was an increase in the number of clusters, mainly due to a reduction in the radius of the conglomerates, a phenomenon influenced by the methodological adjustment. For the number of thermoelectric plants, there were eight clusters, four of which centered in the Southeast, two in the Northeast, one in the South and one in the North. The northeastern coast stood out for its strong influence on energy generation [52], as did the interior of the state of São Paulo [46]. For installed potential, 23 clusters were observed, maintaining the same regions as the number of thermoelectric plants.

Based on the characteristics of the clusters regarding the quantity and installed potential of sugarcane bagasse thermoelectric plants in Brazil in 2017 (Table 5), seven clusters were identified for the number of plants, with only three being statistically relevant. Cluster 1 had a centroid in the municipality of Engenheiro Beltrão (Paraná) with a radius of 298.13 km. There were 72 thermoelectric plants, although only 32 were expected. The RR was 2.49, the highest among the significant clusters. With an LLR of 20.10, cluster 1 was a significant cluster with the lowest chance of occurring by chance.

The second cluster was centered in Palestina (São Paulo), with a radius of 138.64 km, where 58 mills were identified (in the states of Minas Gerais and São Paulo). The municipalities with the most outstanding participation were Ariranha (São Paulo), Catanduva (São Paulo) and Monte Aprazível (São Paulo), with the Catanduva and Nhandeara microregions standing out. Climatic suitability is one of the main factors favoring regional productivity, with rainfall concentrated in the summer and droughts in the winter [56]. The largest power plant was Colombo Ariranha, with 105.5 MW installed, followed by Chapadão Agroenergia (92 MW) and Moema (89 MW). The RR was 2.19.

The third cluster was centered on Paragominas (Pará) and encompassed supply to the coast of the Northeast and the North regions, where supply was distributed

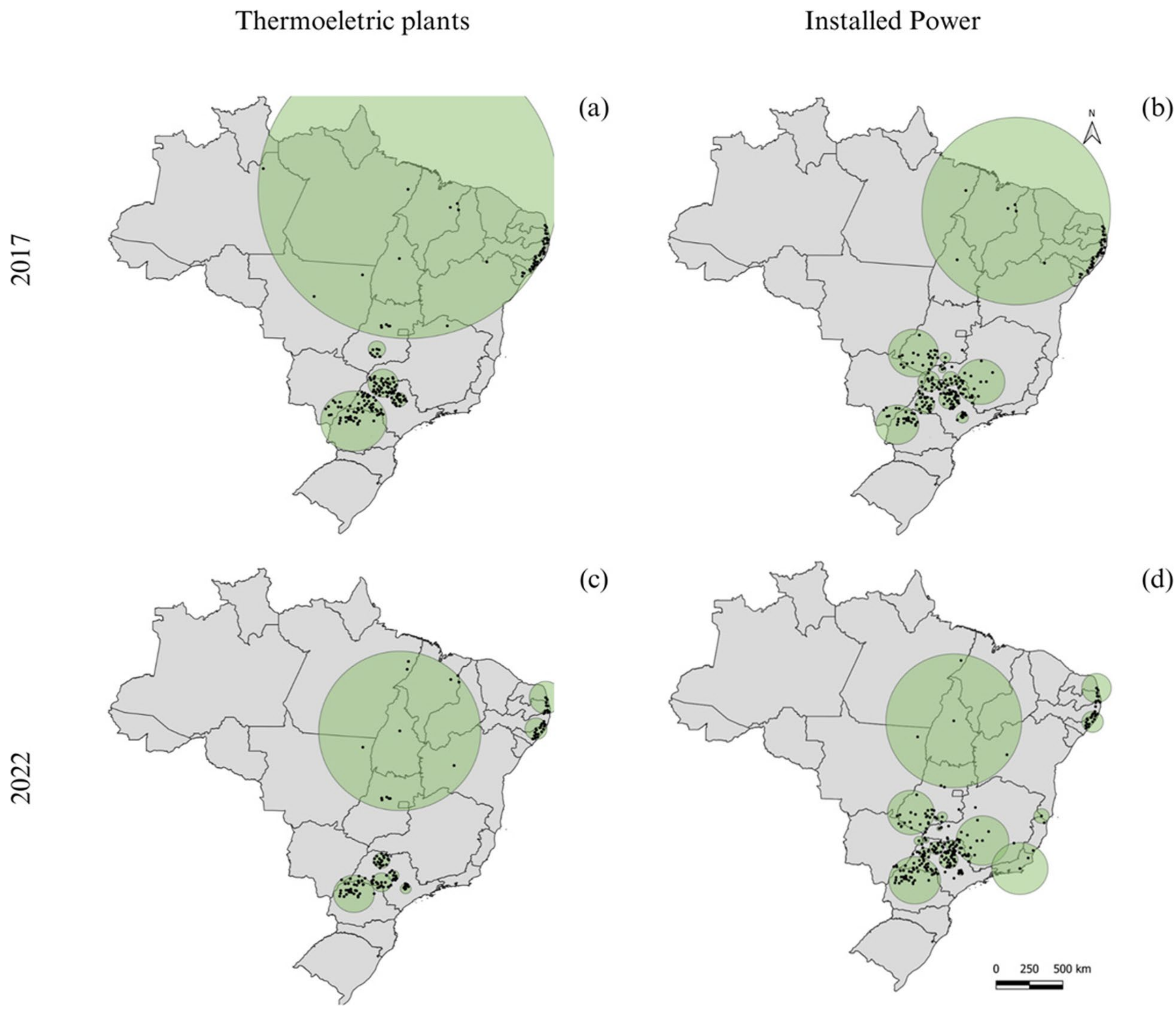

Fig. 3 Clusters of sugarcane bagasse thermoelectric plants and installed capacity (MW) in Brazil, for 2017 and 2022

Table 5 Cluster characteristics of sugarcane bagasse thermoelectric plants in Brazil, for 2017 and 2022

	C	Centroid	R (km)	Obs	Exp	RR	LLR	*p valor*
2017	1	Engenheiro Beltrão—PR	298.13	72	32	2.49	20.10	< 0.001
	2	Palestina—SP	138.64	58	29	2.19	12.61	< 0.001
	3	Paragominas—PA	1478.93	61	32	2.04	11.13	< 0.001
	4	Araraquara—SP	70.29	25	15	1.77	3.25	0.9763
	5	Jandaia—GO	80.71	9	4	2.36	2.50	0.9994
2022	1	Engenheiro Beltrão—PR	184.10	33	13	2.67	11.30	< 0.001
	2	Monte Aprazível – SP	75.61	29	13	2.24	7.03	0.1237
	3	São José da Laje – AL	107.12	21	9	2.53	6.60	0.1537
	4	Goianinha – RN	159.92	11	4	2.69	3.92	0.8815
	5	São Pedro Turvo – SP	92.75	19	10	1.94	3.27	0.9757
	6	Boituva – SP	49.08	11	5	2.28	2.85	0.9976
	7	Bariri – SP	50.23	11	5	2.17	2.56	0.9996
	8	Pedro Afonso—TO	788.26	13	7	2.00	2.46	0.9997

C cluster, *R* Radius, *Obs* Observed cases, *Exp* Expected cases, *RR* Relative risk, *LLR* Likelihood ratio test (LLR) spatially. Sixty-one plants were observed, with the states of Alagoas, Paraíba, and Pernambuco standing out. Only 32 thermoelectric plants were expected based on the number of generators in the region. Clusters 4 and 5, although not statistically significant, highlight areas where the supply of sugarcane biomass is vital for the regional economy. However, sugarcane biomass is not more important than other energy sources, becoming merely complementary.

For 2022, there were eight clusters, which were a dissolution of the previous ones in a smaller area. The most significant cluster remained centered on the municipality of Engenhero Beltrão (Paraná), but with 33 thermoelectric plants, as opposed to the 13 expected, the RR rose to 2.67. Although centered in Paraná, most of the mills were located in the southwest of the state of São Paulo, in the mesoregions of Presidente Prudente and Assis; these regions are highlighted in the work of Abreu et al. [57] as one of the main areas for sugarcane production in Brazil.

The remaining clusters were not statistically significant, but it is important to note their locations: cluster 2 was identified in the interior of São Paulo, and cluster 3 on the coast of the Brazilian Northeast. The decrease in the number of significant clusters is associated with the expansion of electricity generators in the national matrix, with a substantial increase in supply from solar photovoltaics and wind [7]. This effect tends to be reduced from the point of view of installed potential, due to the power density of sugarcane bagasse thermoelectric plants. Table 6 shows the characteristics of the clusters of installed power (MW) of sugarcane bagasse-based thermoelectric plants in Brazil, for 2017 and 2022.

Nine clusters were found for installed potential, all significant based on the p-value. Cluster 1 was centered on the municipality of Perolândia (Goiás), with a radius of 236.12 km. The installed power in this cluster was 1232.88 MW, while 596.89 MW was expected, the relative risk was 2.20, and the LLR 277849.18, making it the most likely to be real.

Corroborating the regional concentration, the state of São Paulo had the highest number of supply centroids, totaling six conglomerates, including the one with the highest RR centered on Nova Independência (São Paulo), with 82.05 MW installed, and an RR of 3.36. Piacente et al. [58] highlighted the availability of land for planting sugarcane as one of the main factors in the growth of the activity in the region, highlighting the strong supply in the mesoregion of Araçatuba, Presidente Prudente and São José do Rio Preto.

Cluster 5 had the highest power output with 1.29 GW, a radius of 22.77 km, and was centered on Bambuí (Minas Gerais). In addition to including several mills in the state of Minas Gerais, the conglomerate also included the complex of mills in the north of the state of São Paulo.

In 2022, the main cluster was centered on Jadaia do Sul, with 237.99 km, and 1.6 GW installed. The power plants were distributed among the states of Mato Grosso do Sul, Paraná and São Paulo. The cluster area encompasses the intermediate region of Campo Grande (Mato Grosso do Sul), which constitutes the *Bolsão Sul-Mato-grossense*, a region linked to the states of São Paulo and Paraná, which can indicate technological spillover between the areas [32].

Two clusters were tied as presenting the highest RR: cluster 10 and cluster 15. Cluster 10 was centered in Santa Albertina (São Paulo) and had 74 MW installed (24 MW from Carneirinho and 50 MW from Colombo Santa Albertina. Although the supply is low compared to other points, the low supply of power around the cluster can characterize this conglomeration. Cluster 15, centered on Serra dos Aimorés in Minas Gerais, showed similar characteristics, with an installed capacity of just 37.20 MW, compared to the 8.97 MW expected from the Dasa plants (4.20 MW) in Minas Gerais and Alcon (33 MW) in Espírito Santo.

In this study, the application of regional (*LQ*), partial [*CR*(k)] and summary indices (HHI' and Gi) proved to be complementary, as these encompassed all the participants in the sector. The simultaneous application of indicators is decisive for drawing relevant conclusions [59].

Santos Junior et al. [40] evaluated the forest bioelectricity sector in Brazil, and some of their conclusions encompass the sugarcane sector. The sector's expansion is related to the search for sustainable energy alternatives, reduction of production costs, and techno-environmental precepts, such as circular economy. The existence of clusters in Brazilian supply has demonstrated the development of bioelectricity on the national scene.

Two changes were essential for the growth of bioelectricity in Brazil: the evolution of electricity sector regulations and the practice of energy auctions. The former enabled the injection of surplus electricity into the grid and increased the number of participants in the sector [56, 59]. Energy auctions have intensified biomass supply [60], expanding projects in the sector, motivating technological improvements and increasing energy efficiency in the associated sectors.

In Brazil, the main risks for investments in bioelectricity are associated with the location of facilities, licensing, and grid connection for isolated areas [40]. Evaluation of the market structure from a spatial point of view, along with the identification of clusters of sugarcane bagasse bioelectricity supply, can help the energy development plan. New projects can be optimized by identifying areas with greater regional and technological development

Table 6 Cluster characteristics of the installed capacity (MW) of sugarcane bagasse thermoelectric plants in Brazil, for 2017 and 2022

	C	Centroid	R (km)	Obs	Esp.	RR	LLR (x 10^3)	*p valor*
2017	1	Perolândia—GO	236.12	1232.88	596.89	2.20	277.85	< 0.001
	2	Perobal—PR	194.61	603.35	206.23	3.04	257.87	< 0.001
	3	União—PI	928.76	766.09	324.88	2.46	225.09	< 0.001
	4	Martinópolis—SP	89.26	633.72	262.01	2.50	194.42	< 0.001
	5	Itápolis—SP	96.51	1291.30	733.80	1.86	187.48	< 0.001
	6	Bambuí—MG	223.77	1058.79	560.37	1.98	187.18	< 0.001
	7	Santa Albertina—SP	100.53	484.72	230.09	2.16	109.53	< 0.001
	8	Campo Florido—MG	71.42	291.03	123.28	2.40	83.51	< 0.001
	9	Tanabi—SP	38.39	198.66	85.19	2.36	55.33	< 0.001
	10	Boituva—SP	53.69	164.22	64.37	2.57	54.41	< 0.001
	11	Nova Independência—SP	29.70	82.05	24.54	3.36	41.66	< 0.001
	12	Ituiutaba—MG	33.66	76.00	23.83	3.20	36.09	< 0.001
	13	Morrinhos—GO	50.05	80.00	35.41	2.27	20.70	< 0.001
	14	Sirinhaém—PE	16.69	38.60	14.26	2.71	14.12	< 0.001
2022	1	Jandaia do Sul—PR	237.99	1601.30	675.17	2.57	492.83	< 0.001
	2	Perolândia—GO	224.12	1338.11	647.99	2.19	300.04	< 0.001
	3	Nova Europa—SP	86.94	1328.47	664.73	2.11	274.46	< 0.001
	4	Lagoa da Prata—MG	249.29	1010.34	496.16	2.12	215.14	< 0.001
	5	Monte Aprazível—SP	65.08	640.46	302.83	2.17	146.65	< 0.001
	6	São Luís do Quitunde—AL	106.54	249.98	67.90	3.73	145.03	< 0.001
	7	Goianinha—RN	147.40	204.50	60.42	3.42	106.06	< 0.001
	8	Pedro Afonso—TO	675.13	260.73	101.30	2.61	88.06	< 0.001
	9	Guaíra—SP	51.25	411.12	224.74	1.86	63.29	< 0.001
	10	Santa Albertina—SP	27.40	74.00	17.84	4.17	49.23	< 0.001
	11	Ituiutaba—MG	23.19	96.00	31.74	3.04	42.16	< 0.001
	12	Capivari—SP	26.54	103.40	37.75	2.75	38.70	< 0.001
	13	Aparecida do Taboado—MS	45.24	52.70	12.71	4.16	35.03	< 0.001
	14	Morrinhos—GO	50.05	85.50	30.57	2.81	33.13	< 0.001
	15	Serra dos Aimorés—MG	73.50	37.20	8.97	4.16	24.72	< 0.001
	16	Pirajuba—MG	11.59	100.00	52.50	1.91	17.03	< 0.001
	17	Cabo Frio—RJ	261.87	56.00	23.60	2.38	16.04	< 0.001
	18	Sud Mennucci—SP	0.78	67.00	32.31	2.08	14.22	< 0.001
	19	Bento de Abreu—SP	53.38	309.05	229.53	1.35	12.66	< 0.001
	20	Nova Independência—SP	7.67	55.00	26.52	2.08	11.67	< 0.001
	21	Goiatuba—GO	23.73	86.52	49.44	1.76	11.39	< 0.001
	22	Tupaciguara—MG	0.09	75.00	44.01	1.71	9.03	< 0.001
	23	Limeira do Oeste—MG	1.69	50.00	26.52	1.89	8.24	< 0.001

C Cluster, *R* Radius, *Obs* Observed cases, *Exp* Expected cases, *RR* Relative risk, *LLR* Likelihood ratio test (LLR)

for bioelectricity generation, reducing investment risks [61, 62]. Brazil's energy development plan emphasizes the importance of biomass thermoelectric power plants within the national matrix. However, new projects and business models must be introduced to enhance the overall operational viability [61].

From the point of view of market concentration, competition between thermoelectric plants occurs due to the large number of players in the sector, attracted by the opportunities to reduce costs and profit from electricity exports. The high level of competition regarding bioelectricity enables new generators to enter the national matrix, with positive effects on the market, avoiding monopoly situations [63].

Regulatory changes in the electricity sector and the creation of government incentives have been decisive aspects in structuring the national bioelectricity sector. Uncertainties have been mitigated, and new investments have been attracted, increasing competition in the electricity market [32]. In addition, the energy transition has resumed after the COVID-19 pandemic, another aspect that tends to intensify the participation of sugarcane bagasse bioelectricity in Brazil [64, 65].

Finally, the methods presented can be used to evaluate the diversity of electricity and energy matrices elsewhere, being useful for investors and policymakers. The methodology proposed herein can also assess other renewable energy supply chains. These applications are still underexplored internationally, and studies from this perspective are just beginning in Brazil.

The contribution of this study is an analysis of the market structure and spatial conglomeration of sugarcane bagasse bioelectricity in Brazil. Identifying regions with spatial concentration and leading producers is extremely useful for future bioelectricity feasibility studies. Studies such as the one presented herein can encourage public policy formulation in areas specialized in bioelectricity, potentially reducing investment costs and boosting the sector's growth. The methodology can be applied in different regions and countries to promote the development of the bioelectricity sector. The benefits of investing in new areas and bioelectricity resources are crucial to strengthening national energy security, and enhancing the diversification and complementarity of the energy matrix.

4 Conclusions

The study presented herein analyzed the location and spatio-temporal concentration and clusters of sugarcane bagasse bioelectricity in Brazil in 2017 and 2022, highlighting the dynamics of supply and the evolution of the use of biomass. The results showed an increase in the use of sugarcane bagasse in the country over five years.

There was a strong concentration between the states regarding the number of mills, especially in the Southeast and Midwest regions. A similar behavior was observed for installed potential. Five clusters were identified for the number of power plants in 2017 (only three were statistically significant), but for 2022, eight clusters were identified (only one remained statistically significant). Regarding installed capacity, there were 14 clusters in 2017 and 23 clusters in 2022, all statistically significant.

At the end of this study, it was possible to understand the spatial distribution of bioelectricity from sugarcane and its market structure in Brazil. These results can potentially inform strategic decisions and guide the formulation of public policies aimed at expanding the sugarcane biomass sector. The results presented herein can be used in subsequent feasibility assessments, especially in cluster regions and surrounding areas. More studies on bioelectricity encourage energy diversification and complementarity within the national electricity matrix, promoting energy security.

Future research can address circular economy practices in industries and assess the impacts of their premises on the process of energy evolution and transition.

Acknowledgements

The authors thank the National Council for Scientific and Technological Development—CNPq (Productivity Research Grants 309452/2021-0 and 310871/2021-2, and Institutional Scholarship Program for Scientific Initiation). Thanks are extended to to the Coordination of the Coordination for the Improvement of Higher Education Personnel—CAPES (MSc. Scholarship 88887571633/2020-00) and the financial supported by Paraíba State Research Support Foundation—FAPESQ.

Authors' contributions

Luiz Moreira Coelho Junior: conceptualization, methodology, formal analysis, writing—original draft preparation, validation, writing—review and editing, supervision, and project administration; Edvaldo Pereira Santos Júnior: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing—original draft preparation; Cleani Figueredo Fideles da Silva: data curation, validation, and writing—review and editing; Brunna Hillary Calixto de Oliveira—data curation, validation, and writing -review and editing; João Batista Cordeiro Dantas—validation, writing—review and editing; Josimar Vieira dos Reis—writing—review and editing; Vanessa Batista Schramm: writing—review and editing, supervision and project administration; Fernando Schramm: writing—review and editing, supervision, and project administration; Monica Carvalho: writing—review and editing, supervision, and project administration. All authors read and approved the final manuscript.

Funding

This work was supported by Paraíba State Research Support Foundation—FAPESQ—Call N 19–2022 Programme to Support Consolidating Nucleus in the State of Paraíba—Project N 057–2023—Market structure and eco-efficiency of the Brazilian supply of sugar-energy bioelectricity.

Availability of data and materials

All data generated or analyzed during this study are open to the public.

Declarations

Competing interests

The authors declare they have no competing interests.

Received: 20 December 2023 Accepted: 17 July 2024
Published online: 25 July 2024

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