Programa de Pós-Graduação
Desenvolvimento Regional
Mestrado e Doutorado

DOI: 10.17058/1n73z037

Biomass and Aviation Biofuel Production: Regional Perspectives in Brazil

José Ricardo de Santana
Departamento de Economia, Universidade Federal de Sergipe, Sergipe, Brasil. E-mail: jrsantanaufs@gmail.com
ORCID: https://orcid.org/0000-0001-5617-2096

Lindomayara França Ferreira
Departamento de Economia, Universidade Federal Juiz de Fora, Minas Gerais, Brasil. E-mail: lindomayara@hotmail.com
ORCID: https://orcid.org/0000-0001-7014-4294

Marcelo da Costa Mendonça
Faculdade Tiradentes. E-mail: marcelo_costa@unit.br
ORCID: https://orcid.org/0000-0001-6003-4796

Claudio Dariva
Faculdade Tiradentes. E-mail: claudio.dariva@gmail.com
ORCID: https://orcid.org/0000-0002-5239-9039

Abstract
Faced with the challenges of decarbonization, a series of international agreements have sought to mitigate the problem, focusing on the most critical areas. In the transport sector, where there are high levels of CO2 emissions, Brazil has developed policies and instruments aimed at producing sustainable fuels from biomass. The legislation under discussion in the country seeks to expand the production of sustainable fuels for current segments and start production in new segments, such as aviation, from 2027, to meet the Sustainable Development Goals (SDGs). Considering the Brazilian experience of producing vehicle biofuel from sugarcane biomass, this raw material has been identified as a viable route for the production of Sustainable Aviation Fuel (SAF) in the country. With a preliminary estimate of the requirements for SAF production in Brazil to comply with legislation, this article aims to identify locations in Brazilian regions with the potential to meet future demands for sustainable biofuels for aviation, using sugarcane bagasse. From the construction of the Locational Quotient (LQ) specialization indicator for biomass production in each state of Brazil, in addition to the states with the highest production volumes – São Paulo, Minas Gerais, Goiás, and Mato Grosso do Sul – a concentration was identified in the Northeast region of the country, especially in the states of Alagoas, Pernambuco and Paraíba. These results highlight locations with pre-established capacities to support the production of SAF,

providing important information for government planning of future demands in the transport sector, considering possibilities to mitigate regional disparities.

Keywords: Decarbonization; Sugar cane; Sustainable Aviation Fuel.

1 Introduction

In recent years, there has been an intense debate about the urgency of global decarbonization and the transformation of carbon-intensive sectors. With targets established by the United Nations (UN) at the Conferences of the Parties (COP), different economies have adopted policies and measures aimed at reducing emissions by 2050 (IRENA, 2023).

Among the strategies to reduce emissions is the prioritization of actions in certain sectors that make intensive use of fossil fuels. One of these is transportation (including land, air, and maritime modes), with estimates indicating a reduction in emission levels from 8.1 $GtCO_2$ in 2019 to 0.4 $GtCO_2$ in 2050. The most promising alternative to produce renewable fuel is the use of biomass, which is an organic material which can be used to generate thermal energy, electricity, and fuels, constituting a clean, sustainable, and renewable resource. In 2019, bioenergy from solid biomass, biogas, and liquid biofuels accounted for about 9% of the total global supply of primary energy, especially for industry and the transportation sector. In a scenario aimed at limiting the temperature increase to 1.5°C above pre-industrial levels, bioenergy is expected to represent 17% of the global supply of primary energy by 2030, and the production of liquid biofuels is estimated to grow roughly fivefold by 2050. This would correspond to 25% of global energy demand in the transportation sector. However, these estimates highlight the major challenge, namely, the need to increase biomass production to meet future demand in the transportation sector while avoiding adverse environmental or social impacts (IRENA, 2021; 2022).

With technological availability and reduced production costs, the substitution of fossil fuels with bioenergy has increased, especially in carbon-intensive activities. However, in the aviation market, fuel from renewable sources remains relatively unexplored. A recent alternative to reducing CO_2 emissions in the transportation sector by up to 87% is the development of Sustainable Aviation Fuel (SAF) (WATSON et al., 2024). According to IRENA (2022), aviation will require about 82 billion liters of biofuels annually by 2030. In Brazil, where vehicle ethanol has long been produced from sugarcane (a renewable fuel), there is considerable availability of this biomass for the transportation sector and for aviation biofuel production.

Although still incipient, Brazil has developed initiatives aimed at the aviation sector to meet its decarbonization goals and the Sustainable Development Goals (SDGs) established at COP 26 (IRENA, 2024). Predominantly derived from fossil sources, in 2022 Brazil's production of aviation fuels reached 4.9 million m^3, representing about 5% of the country's petroleum-derived fuel output (ANP, 2023). Brazil has consolidated experience in biofuel production, especially ethanol from sugarcane, which has been one of the most successful policies for producing and distributing biofuels for motor vehicles (MILANEZ et al., 2021). Considering the well-established ethanol production chain in the country, the biomass generated as residue from this activity represents an attractive opportunity for the development of the SAF industry. Sugarcane bagasse is the main source of biomass available in Brazil, accounting for more than 71% of the feedstock used for fuel production, followed by forest-based sources (black liquor byproduct from the pulp industry, forest residues, and firewood), which account for over 25% (ANEEL, 2023).

In this context, it is important to analyze the Brazilian case within this international effort given the country's relevance and potential in the process of mitigating CO_2 emissions. However, it is also necessary to investigate how this opportunity to produce renewable aviation fuels will influence biomass production across Brazilian regions. Thus, based on preliminary estimates of the bio-kerosene production needs in Brazil, this article aims to identify the locations within Brazilian regions that have the potential to meet future demand for sustainable aviation biofuels using sugarcane bagasse. By constructing a specialization indicator, the Location Quotient (LQ), for biomass production (GW) in each state of Brazil, a productive concentration in the Northeast region was identified. This is one of the poorest regions of the country, especially the states of Alagoas, Pernambuco, Paraíba, Rio Grande do Norte, and Sergipe. Other states with high levels of specialization were also identified and they include São Paulo, Minas Gerais, Goiás, and Mato Grosso do Sul. This leads in the volume of energy production from sugarcane biomass (kW) and in the number of operating facilities.

This study is structured into five sections, including the introduction and final conclusions. The second section discusses policies and incentive instruments aimed at the transportation sector, specifically the sustainable agenda for aviation activities in Brazil. The third section presents the composition and data sources used to estimate bio-kerosene production and construct the Location Quotient (LQ). Finally, the fourth section presents the production estimates, maps of sugarcane production, and maps of the LQ results, in addition to discussing the main implications for the productive development of SAF in Brazil and the country's ability to meet future demand.

2. Decarbonization and regional possibilities for bio-kerosene production in Brazil

This section aims to discuss the challenges of the global decarbonization process as well as the strategies targeted at the transportation sector, particularly activities involving biofuels. It is divided into two subsections: (i) perspectives on decarbonization and the role of biofuels, with an emphasis on regional discussion; and (ii) initiatives aimed at expanding the use of biofuels, including in the aviation sector, in Brazil.

2.1 Challenges of decarbonization and biofuels

The intense debate on the urgency of mitigating anthropogenic climate change has been fostered since the 1990s, as highlighted in Table 1. With the Kyoto Protocol and the Paris Agreement under the Conferences of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations 2030 Agenda established targets to promote sustainable development and cooperation agreements among countries, particularly industrialized nations.

Table 1: Conference of the Parties to the Framework Convention (COP), (1995-2023)

Conference	Country (year)	Emphasis
1st COP	Berlin, Germany (1995)	Negotiation of specific targets and deadlines for the reduction of greenhouse gas emissions by developed countries.
2nd COP	Geneva, Switzerland (1996)	Decision to create legal obligations for reduction targets.
3rd COP	Kyoto, Japan (1997)	The creation of the Kyoto Protocol, which established reduction targets for greenhouse gas emissions for developed countries.
4th COP	Buenos Aires, Argentina (1998)	Implementation and ratification of the Kyoto Protocol.
5th COP	Bonn, Germany (1990)	Discussions about activities for removing carbon dioxide from the atmosphere, such as afforestation and reforestation.
6th COP-I	The Hague, Netherlands (2000)	Discussions on the Clean Development Mechanism, carbon markets, and financing for developing countries.
6th COP-II	Bonn, Germany (2001)	United States withdrawal from the Kyoto Protocol.
7th COP	Marrakech, Morocco (2001)	Decision to limit the use of carbon credits generated from forestry projects and the establishment of aid funds for developing countries.
8th COP	New Delhi, India (2002)	Beginning of the discussion on the use of renewable sources in the energy matrix.
9th COP	Milan, Italy (2003)	Discussion of regulations within the framework of the Clean Development Mechanism.
10th COP	Buenos Aires, Argentina (2004)	Approval of rules for the implementation of the Kyoto Protocol.
11th COP	Montreal, Canada (2005)	For the first time, the debate is on tropical deforestation and changes in land use.
12th COP	Nairobi, Kenya (2006)	Review of the Kyoto Protocol and rules for project financing.
13th COP	Bali, Indonesia (2007)	For the first time, the issue of forests is included in the text of the Conference's final decision.
14th COP	Poznan, Poland (2008)	Discussion of a possible global climate agreement.
15th COP	Copenhagen, Denmark (2009)	The most important of the multilateral environmental agreements, establishing the treaty that replaces the Kyoto Protocol.
16th COP	Cancun, Mexico (2010)	Creation of the Green Climate Fund.
17th COP	Durban, South Africa (2011)	It brought together more than 190 countries, with commitments to action to curb the rise in global temperatures.

18th COP	Doha, Qatar (2012)	Extension of the Kyoto Protocol.
19th COP	Warsaw, Poland (2013)	Creation of a "carbon currency" to reward countries that reduce their greenhouse gas emissions.
20th COP	Lima, Peru (2014)	Presentation of the emission reduction and climate change adaptation commitments of 195 countries.
21st COP	Paris, France (2015)	For the first time, almost all countries were making an effort to reduce carbon emissions and contain the effects of global warming.
22nd COP	Marrakech, Morocco (2016)	Focus on actions related to adaptation, transparency, technology transfer, mitigation, capacity building, and loss and damage.
23rd COP	Bonn, Germany (2017)	Renewable energy targets and increased funding for climate adaptation.
24th COP	Bonn, Germany (2017)	It establishes how governments would measure and report their emissions reduction efforts.
25th COP	Madrid, Spain (2019)	In the field of science, the inclusion of issues such as oceans and land use, and the approval of a new Gender Action Plan.
26th COP	Glasgow, Scotland (2020)	Promise of a gradual elimination of fossil fuels.
27th COP	Sharm el-Sheikh, Egypt (2021)	Creation of a fund for "losses and damages".
28th COP	Dubai, United Arab Emirates (2023)	Transitioning to renewable energy and building climate resilience.

Source: Authors' own, based on MMA (2024).

At COP 26, in Scotland in 2021, the transformation of the transportation matrix was identified as one of the main strategies for advancing the decarbonization process. The goal is to reduce net carbon dioxide (CO_2) emissions to zero by 2050 and to limit the increase in global temperature to 1.5°C above pre-industrial levels (1850–1900) (IRENA, 2023). According to the ITF (2021), the transportation sector is the most emission-intensive in final energy use, responsible for more than 25% of direct CO_2 emissions from fuel combustion. For SEEG (2023), the world's largest CO_2 emitters include China, the United States, India, Russia, Indonesia, and Brazil – the latter accounting for about 3% of global emissions. A significant share of these emissions is concentrated in energy-related activities and in the intensive use of fossil fuels (IRENA, 2024).

Although advances have been made in the use of renewable fuels in the transportation sector, particularly in road transport, changes in the aviation sector remain a major challenge. Targets established for aviation activities in countries with more than 0.5% participation in emissions deserve particular attention. According to Watson et al. (2024), starting in 2027 the sector will undergo a transformation involving compensation mechanisms (through the purchase of carbon credits) and emission reduction measures (such as the use of sustainable fuels), as introduced by the International Civil Aviation Organization (ICAO) through the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (ANAC, 2019).

In Brazil, the transportation sector is one of the key areas for reducing air pollution. In 2022, emissions from the transportation sector reached 210 million tons (Mt) of CO_2 equivalent, representing around 50% of the country's total emissions and surpassing the emission levels of industry, at 76 Mt of CO_2 equivalent (EPE, 2023). Since the 1970s, the country has proposed and implemented programs to reduce the use of fossil fuels in transportation, such as the National Alcohol Program (Proálcool) in 1975, the National Program for the Production and Use of Biodiesel (PNPB) in 2004, and more recently the National Bio-Kerosene Program and the National Biofuels Policy (RenovaBio) in 2021 (BRASIL, 2017).

Biomass – considered an organic, clean, sustainable, and renewable resource – can be produced from sugarcane bagasse, black liquor from the production of wood pulp, forest residues, urban waste, and firewood. It plays a promising role in the Brazilian energy industry. In 2016, biomass from these sources supplied more than 39% of total energy consumption and more than 17% of transportation energy demand in Brazil (GREENPEACE BRASIL, 2016). Used mainly for electricity generation and biofuel production, biomass activities are concentrated in the states of São Paulo (7.5 GW), Minas Gerais (2.3 GW), and Mato Grosso do Sul (2.3 GW). Additionally, more than 420 facilities produce energy from sugarcane bagasse, concentrated in the states of São Paulo, Minas Gerais (Southeast), Paraná (South), Mato Grosso do Sul and Goiás (Center-West), and Alagoas and Pernambuco (Northeast) (ANEEL, 2024).

Brazil is the world's largest producer of sugarcane, and the country has enormous potential to use this as one of its main biomass sources (IRENA, 2023). With production predominantly concentrated in the South and Southeast regions, the growing demand for biofuels may serve as an opportunity to develop policies with multiple impacts, enabling the exploration of transition processes in other regions with significant potential. In other words, policies could be designed not only to promote decarbonization of the transport sector but also to attract investment and generate income and employment in economically less-developed regions, such as the North and Northeast.

It is important to note that the expansion of sugarcane cultivation was shaped by existing soil and climate conditions and by the Proálcool program (1975–1980). The program was initially designed to reduce regional disparities within the country; however, it ended up focusing primarily on economic issues while neglecting environmental sustainability aspects (ALBUQUERQUE et al., 2022). According to Cortez et al. (2016), between 1975 and 1985, Brazil experienced rapid growth in ethanol production and substitution for gasoline, with almost half of sugarcane production concentrated in the Northeast. However, after the end of Proálcool in 1989, the sector faced imbalances due to overproduction of sugar and an low demand for ethanol crisis. Between 2003 and 2008, the sector regained momentum with the introduction of flex-fuel vehicles. Nonetheless, after 2009, a new crisis emerged, marked by productivity losses and the absence of more effective government policies.

Reducing regional inequalities remains a major challenge in Brazil. The North and Northeast regions have historically been marked by significant economic and social disparities (LEAL et al., 2021), rooted in long-standing unfavorable productive structures (SOUZA et al., 2022). With the decline of the sugarcane cycle – previously concentrated in the Northeast – and the rise of gold and coffee cycles in the Southeast, the negative impacts of the transition from an agro-export model to an industrial model persist today, reflected in disparities in basic infrastructure, logistics capacities, and educational systems (POCHMANN; SILVA, 2020). Therefore, these regional differences largely stem from historical economic organization and local development patterns (SOUZA et al., 2022).

Although they have smaller productive capacities compared to the South and Southeast, the North and Northeast – comprising 16 states – have small- and medium-scale biomass production chains today. As highlighted by data from Aneel (2024), biomass production takes place in 13 states in this region: Bahia, Alagoas, Pernambuco, Maranhão, Paraíba, Rio Grande do Norte, Sergipe, Acre, Pará, Amazonas, Roraima, Rondônia, and Amapá. According to IRENA (2021), one of the key characteristics of biomass feedstocks is their low energy density, which makes long-distance transportation economically challenging. Moreover, the novelty of the sector (in its early stages) may lead to higher costs compared to traditional fuel routes.

This context is also characterized by market fluctuations linked to short-term policies and inadequate systemic structuring and the fact that the transition to a low-carbon economy may intensify existing disparities. This may occur not only at the regional level but also internationally, placing Brazil at a disadvantage relative to leading global markets and potentially limiting the country to the role of raw-material exporter. As a country with vast agricultural land, favorable natural conditions, and a trained workforce, Brazil has a major opportunity to develop a large-scale renewable fuel industry (CORTEZ et al., 2016). Considering biomass production conditions and the location of industrial units for biofuel manufacturing, there is also potential for policies aimed at regional development, providing opportunities for less-developed areas of the country.

2.2 Programs to expand the use of biofuels in Brazil

Given the multiple challenges identified, it is necessary to develop and optimize the production chain in order to achieve the benefits of economies of scale, including technological development of the activity and the establishment of processing infrastructure. This will require a supportive political framework and instruments aimed at both supply and demand in the sector.

In Brazil, the tradition of committing to international agreements on environmental preservation has materialized in specific policy measures. In the transportation sector, the main measures are related to fuel policy. Table 2 presents some of the main laws implemented in the country since 1993. Law No. 8,723 of 1993 already promotes the reduction of pollutant emissions from motor vehicles, initially focusing on passenger vehicles. Other complementary measures relate to the regulation of energy policy (Law No. 9,478 of 1997) and sector oversight (Law No. 9,847 of 1999). Also noteworthy is the legislation mandating the addition of biodiesel to commercially sold diesel fuel (Law No. 10,033 of 2014), demonstrating an expansion in the scope of fuel regulation to include freight vehicles.

Table 2: Initial legislation related to the implementation of decarbonization measures, focusing on the transport sector – Brazil, 1993-2014

Year	Legislation / Theme
1993	**Law nº 8.723, of October 28, 1993** Reduction of pollutant emissions from motor vehicles and other measures
1997	**Law nº 9.478, of August 6, 1997** National energy policy and establishes the National Council for Energy Policy and the National Petroleum Agency
1999	**Law no 9.847, of October 26, 1999** Supervision of activities related to the national fuel supply
2014	**Law nº 13.033, of September 24, 2014** Mandatory addition of biodiesel to diesel oil sold to the final consumer

Source: Authors' own.

Brazil has reaffirmed its international cooperation agreements for environmental preservation through measures aimed at increasing the use of a clean energy matrix based on renewable sources. Recently, actions in this direction have been implemented, as reflected in the National Biofuels Policy – RenovaBio (Law No. 13,576 of 2017) and the establishment of the Green Mobility and Innovation Program – MOVER (Provisional Measure No. 1,205 of 2023). In addition, the Future Fuel Program (Bill No. 528 of 2020) is currently under review in the National Congress. Table 3 presents these initiatives and their respective objectives.

Table 3: Recent initiatives to encourage the use of sustainable fuels – Brazil, 2017-2024

Program	Objectives
National Biofuels Policy - RenovaBio (Law No. 13,576/2017)	i. To contribute to meeting the commitments of the Paris Agreement, Convention on Climate Change ii. To contribute to the reduction of greenhouse gas emissions iii. To promote the expansion of the production and use of biofuels in the national energy matrix iv. To contribute to the reduction of greenhouse gas emissions
Green Mobility and Innovation Program - MOVER (MP nº 1.205/2023)	i. Support decarbonization, with measures in the vehicle production chain. ii. Support technological development, competitiveness, and integration into global value chains.
Future Fuel Program (Bill No. 528/2020)	i. Establish sustainable fuel programs ii. Change limits on sustainable fuels in blends with fossil fuels iii. Regulate carbon capture activities and the commercialization of synthetic fuels iv. Integrate initiatives adopted in federal programs - RenovaBio, Mover, PBEV

Source: Authors' own.

RenovaBio clearly states among its objectives the reduction of greenhouse gas emissions, highlighting the importance of promoting the production and use of biofuels in the national energy matrix. The MOVER Program reinforces the focus on decarbonization by supporting technological development within the vehicle production chain. In turn, the Future Fuel Program aims to expand the use of sustainable fuels in various segments – including blending with fossil fuels – and to regulate carbon capture activities, while also seeking to integrate ongoing Federal Government initiatives such as RenovaBio and MOVER.

The Future Fuel Program consists of a set of other programs, including: (i) the National Decarbonization Program for Natural Gas Producers and Importers and the Incentive Program for Biomethane; (ii) the National Green Diesel Program (PNDV); and (iii) the National Sustainable Aviation Fuel Program (PROBIOQAV). These are presented in Table 4.

Table 4: Initiatives of the Fuels of the Future Program – Brazil

Programs	**Objectives and Measures**
National Program for Decarbonizing Natural Gas Producers and Importers and Promoting Biomethane Production	a) Decarbonization of Natural Gas Producers and Importers and Incentives for Biomethane. b) Encourage research, production, marketing, and use of biomethane and biogas in the Brazilian energy matrix with a view to decarbonizing the natural gas sector. c) Reduction of pollution through greenhouse gases. d) Regulates the exercise of carbon dioxide capture activities for geological storage purposes. e) Gradual decarbonization of gasoline, with the addition of ethanol. f) Increases the percentage of alcohol added to gasoline.
National Green Diesel Program (PNDV)	a) Gradual decarbonization of diesel fuel through the addition of biodiesel to its composition. *b)* Encourage research, production, marketing, and energy use of green diesel, as established in ANP regulations, within the energy matrix.
National Sustainable Aviation Fuel Program (PROBIOQAV)	a) Gradual decarbonization of fuel used in Brazilian aviation. *b)* Encourage research, production, marketing, and energy use of sustainable aviation fuel (SAF) in the Brazilian energy matrix.

Source: Authors' own.

The Future Fuel Program seeks to intensify decarbonization efforts across three fronts: (i) increasing the use of ethanol in gasoline, encouraging the use of biomethane, and seeking to regulate carbon capture; (ii) expanding actions in the freight transport segment by promoting the use of biodiesel (PNDV); and finally (iii) covering the aviation segment by following a global trend and encouraging research, production, and use of aviation bio-kerosene (PROBIOQAV).

3. Methodological procedures

This section aims to present the methodological procedures used in this study. First, it outlines the procedures applied to estimate SAF and biomass production in Brazil, and subsequently, the construction of a regional specialization indicator, along with the database and its respective sources.

3.1 Estimated production of agroforestry systems and biomass in Brazil

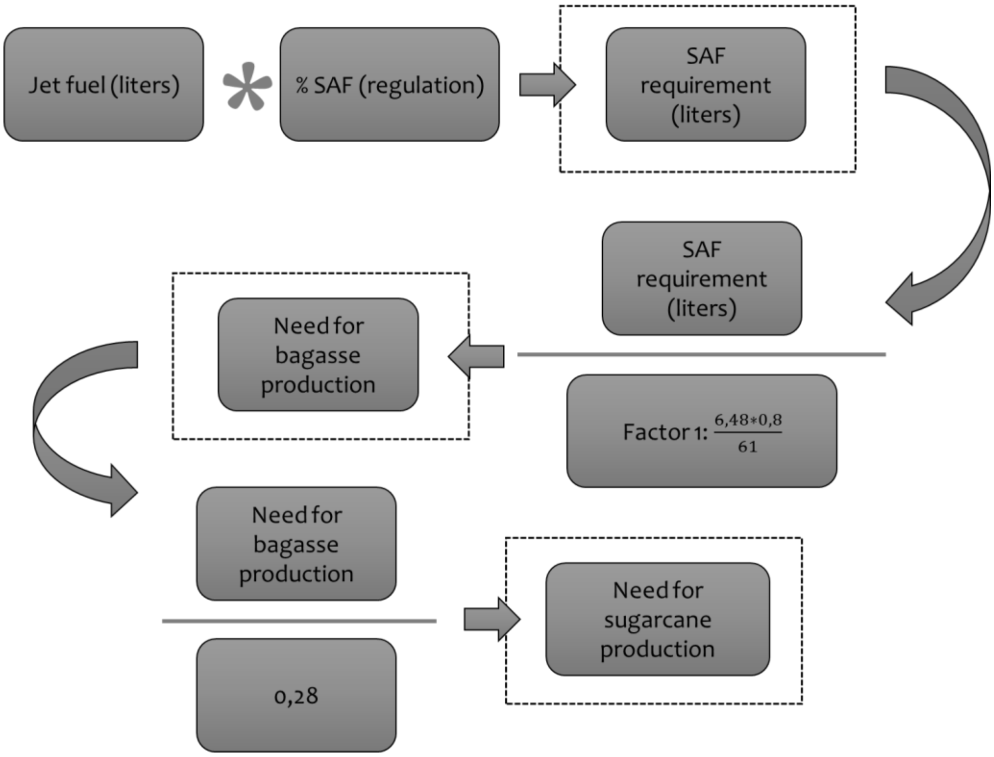
In Brazil, in 2015, 65% of the aviation fuel consumed was associated with international travel (PROQR, 2022). With the global agenda for sectoral decarbonization beginning in 2027, the addition of SAF in aviation fuel in Brazil will be subject to a minimum requirement established by domestic legislation, with a progressively increasing blending mandate in order to meet the targets set by the international CORSIA agreement. This volume is directly linked to the country's biomass production, in which sugarcane stands out as the main feedstock, accounting for 82% of all biomass used nationwide (ANEEL, 2024).

An estimate of sugarcane production destined for SAF generation was carried out in three steps:

i. A conversion factor from Dantas Filho (2019) was considered, which estimates that 28% of sugarcane production results in bagasse, thereby determining the amount of sugarcane biomass required to produce the necessary biomass to convert into SAF.
ii. Another conversion factor, a ratio of 0.10623 presented by Milanez et al. (2021), was used to identify the relationship between SAF volume and the amount of sugarcane biomass required to meet domestic demand for the period between 2027 and 2037.
iii. The required SAF volume was identified based on domestic aviation kerosene production (ANP, 2023), relating it to the blending percentages mandated by Brazilian legislation starting in 2027 (BRASIL, 2024).

This information made it possible to determine the required sugarcane production in the country to comply with government commitments. Using this same ratio, the biomass production capacity in each region was estimated based on the sugarcane output, as illustrated in Figure 1.

Figure 1: Procedures used



Source: Authors' own.

Based on these preliminary estimates, it was possible to outline the scenario for SAF production in Brazil, considering the use of sugarcane biomass to meet the country's future SAF demand between 2027 and 2037.

Additionally, sugarcane production was mapped across the different regions of the country, identifying the output in each state based on data from IBGE (2017). Using these data, the regions and states with the potential to meet the required sugarcane biomass demand – needed to supply national SAF production as established by Brazilian legislation currently under implementation – were identified.

3.2 Regional specialization of energy production from biomass (LQ)

The subsequent stage of the methodology considered data related to the potential for energy production from sugarcane biomass. For this, data on authorized energy generation from sugarcane bagasse were used, representing the official permits for producing energy from biomass. To identify each state's production potential, the Location Quotient (LQ) indicator was used.

The LQ indicator is a tool used to identify patterns of spatial concentration or dispersion of regional activities within an economy. Easily adaptable to different themes, indicator-based analysis generally maps important information (MONASTERIO, 2011). In the present study, the LQ was constructed using data on authorized generation capacity from biomass (GW) and the total sum of renewable energy sources (GW) for all Brazilian states. It was calculated as described in Equation 1.

$$LQ = \frac{\frac{PRODBiomass\ State}{PRODrenewable\ state}}{\frac{PRODBiomass\ Brazil}{PRODrenewable\ Brazil}} \quad (1)$$

The results of LQ are interpreted based on value 1, following adaptations from Haddad (1989). When the result of the equation is greater than 1, the state is considered relatively more important in the activity compared to the national context. However, although the LQ is a simple calculation, its scale interpretation requires careful consideration. Thus, using a three-level scale, the following relationship applies:

- $0 < LQ < 0,5$ for non-specialized states.
- $0.5 < LQ < 1$ for states that show evidence of specialization in biomass.
- $LQ \geq 1$ for states with a high degree of specialization.

Finally, to construct the indicators and carry out the analyses, a set of secondary data was compiled using information provided by the Brazilian Electricity Regulatory Agency (ANEEL) for the year 2023. In addition, to estimate production under different scenarios (current plan, medium-term, and long-term), data made available by the National Agency for Petroleum and Gas (ANP) and the Energy Research Company (EPE) were used.

4. Results Analysis

This section aims to map and discuss the results obtained from the estimated scenarios of SAF production in Brazil and from the regional specialization indicator, the LQ. In addition, some policy proposals will be presented to help leverage the potential associated with future market demand.

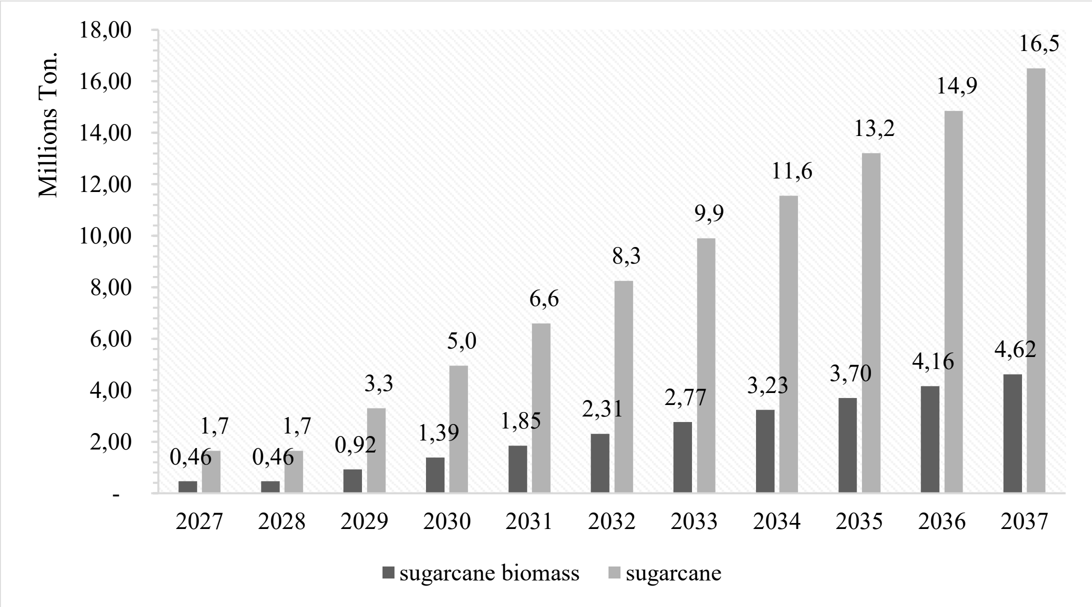
4.1 Prospects for SAF production and biomass needs in Brazil

According to data from EPE (2022), Brazil had 361 sugar–ethanol production units in operation in 2020, with an annual crushing capacity of about 745 million tons and an effective crushing volume of 663 million tons. It is estimated that this process generated around 186 million tons of sugarcane bagasse, considering a residue output of approximately 28%, as estimated by Dantas Filho (2009). This amount could generate up to roughly 19 billion liters of SAF, using 0.1063 as the conversion factor referenced by Milanez et al. (2021).

The regulatory framework currently under discussion in the country was taken as a reference. It establishes an initial target of using 1% renewable sources in fuel composition starting in 2027, increasing progressively to reach 10% by 2037. Considering domestic aviation kerosene production of 4.908 billion liters in 2022, and assuming production remains stable, approximately 49.09 million liters of SAF would have to be produced domestically to supply the aviation sector as early as 2027. This volume is expected to reach a total of 490.89 million liters by 2037, given the 10% blending requirement.

Producing this amount of SAF would require the use of 460 thousand tons of sugarcane bagasse. This volume of biomass could be obtained from the production of 1.7 million tons of sugarcane, which represents 0.25% of the total production available in the country. Figure 2 shows this evolution between 2027 and 2037.

Figure 2: Projected Sugarcane and sugarcane biomass requirements for SAF production – Brazil, 2027-2037 (millions of tons)



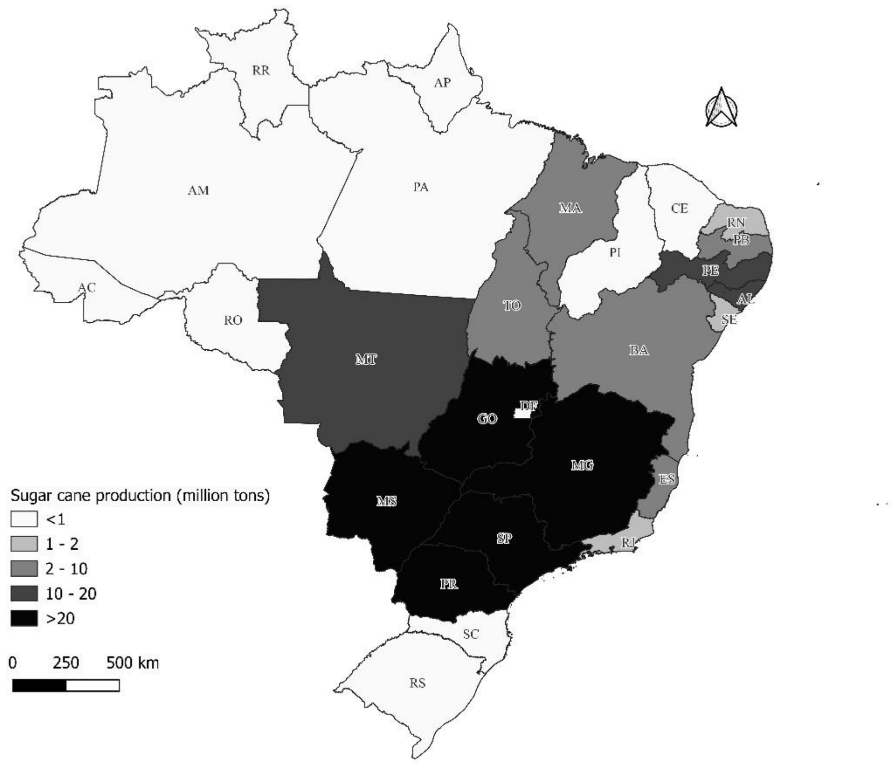
Source: Authors' own.

The data indicates a significant increase in the demand for sugarcane biomass by 2037 if the country chooses this feedstock for SAF production in order to comply with the regulation currently under discussion in the National Congress. Brazilian regulation establishes a blending requirement for aviation kerosene used domestically, starting with 1% SAF in 2027 and reaching 10% SAF by 2037. Even assuming stable aviation kerosene sales, the increase in the SAF blending percentage – considering a production pathway based on sugarcane biomass – will lead to a rise in biomass demand, from 460 thousand tons in 2027 to 4.62 million tons in 2037.

Assuming current production systems remain unchanged, the demand for sugarcane bagasse will also require a growing share of agricultural output. In 2027, meeting the target would require bagasse derived from the production of 1.7 million tons of sugarcane. By 2037, 16.5 million tons of sugarcane would be needed to supply the 4.62 million tons of bagasse required to produce 490.89 million liters of SAF.

Regarding local sugarcane production capacity, Figure 3 illustrates production levels in the 2017 harvest, measured in millions of tons. According to data from the IBGE Census (2017), considering the demand for 1.7 million tons of sugarcane in 2027, several states alone across the South, Southeast, Center-West, and Northeast regions would be capable of meeting the entire national requirement.

Figure 3: Sugarcane production (millions of tons)



Source: Prepared by the authors, based on data from IBGE (2017).

To meet the estimated demand of 16.5 million tons of sugarcane in 2037, the states of São Paulo and Minas Gerais (Southeast), Paraná (South), and Mato Grosso do Sul (Center-West) would be the ones with pre-existing installed capacities capable of supplying the entire national demand on their own. In the Northeast region, the states of Alagoas and Pernambuco combined, would be able to meet the estimated demand.

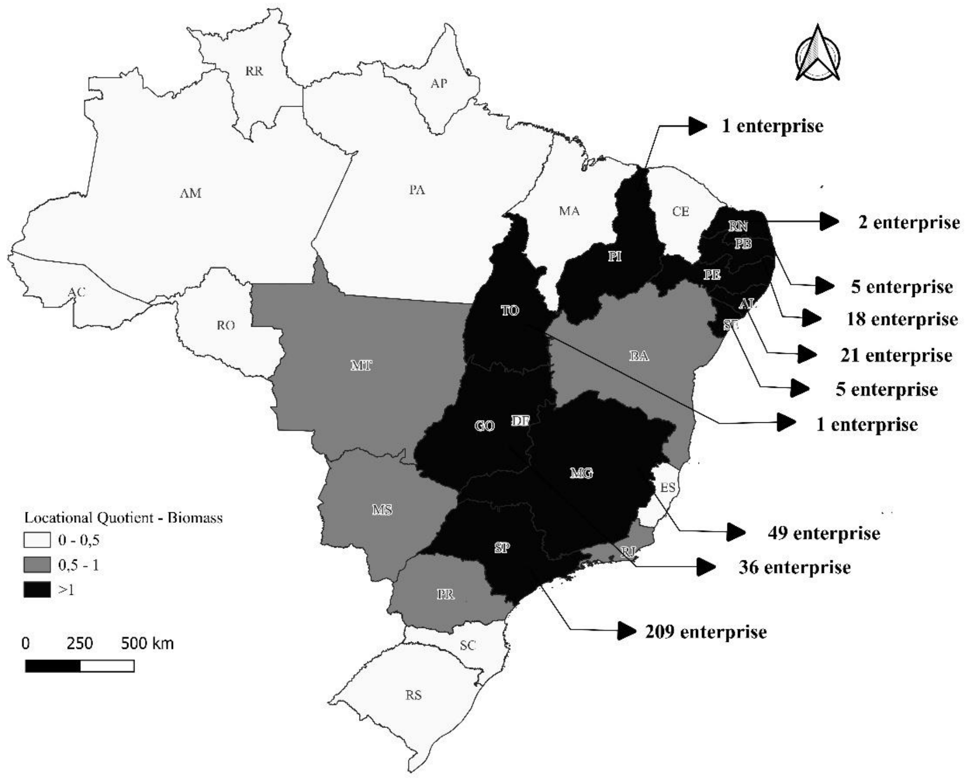
Overall, as previously highlighted, there is a global market signaling future demand for sustainable biofuels. Brazil not only has the potential to benefit from this boom, given its availability of agricultural land suitable for producing biomass from sugarcane, but it can also foster the development of productive chains with high added value in the country’s Northeast region, with potential to generate employment and income from the local bioeconomy. However, to reap the benefits associated with this market, the development of adequate infrastructure, refineries, and projects aimed at improving kerosene conversion in engines is essential, namely the development of a domestic industry in the sector.

There are clear indications of the emergence of this market in Brazil, driven by international regulations and domestic standard-setting, especially with the creation of the Future Fuels Program (CNPE Resolution No. 7/2021) and the regulation of the National Sustainable Aviation Fuel Program (Bill No. 4,516/2023), as previously mentioned. This movement is expected to boost the production of feedstocks for renewable fuel manufacturing, stimulating the economy in regions with greater potential for producing these raw materials.

4.2 Potential for energy production from sugarcane biomass: regional availability

This increase in SAF production to meet the aviation kerosene blending requirements established by domestic legislation starting in 2027 may generate regional opportunities. In this context, it is important to identify the main sugarcane-producing areas – given that sugarcane is the most relevant biomass source in the Brazilian case – and to map the locations that are authorized to produce energy from this biomass.

Figure 4: Location Quotient of Biomass Production from Sugarcane



Source: Authors' own, based on data from ANEEL (2024).

Although the state of São Paulo stands out as the location with the largest production volume (6,306,548.2 kW), followed by Minas Gerais (1,649,920 kW), Goiás (1,474,068 kW), and Mato Grosso do Sul (1,159,409 kW), the mapping of feedstock productivity and existing cultivation areas indicates a productive specialization in the states of Brazil's Northeast region. This is also a region characterized by high levels of renewable energy generation (wind, solar, and hydro). Among the states in the Northeast, the following stand out: Alagoas (357,462 kW), Pernambuco (317,575 kW), Paraíba (101,500 kW), Rio Grande do Norte (61,000 kW), and Sergipe (59,700 kW), as shown in Figure 4.

Results with LQ > 1 (greater than one) may be interpreted as indicating that the region is relatively more important in the national context to produce biomass from sugarcane biomass. Therefore, these states can be identified as units with pre-established capacities capable of meeting the future demand of the SAF market.

The results also point to signs of specialization in the following states: Rio de Janeiro (49,000 kW), Mato Grosso do Sul (1,159,409 kW), Paraná (592,640 kW), Bahia (22,000 kW), and Mato Grosso (9,400 kW). In this context, these states have potential to develop biomass production activities based on sugarcane.

Considered a region of strong economic performance, the South–Southeast region concentrates the highest number of agro-industrial enterprises involved in biomass production from sugarcane. In 2023, the state of São Paulo recorded a Gross Domestic Product (GDP) of R$ 2,719,751 million and a total of 209 biomass production facilities in operation. The state of Minas Gerais recorded a GDP of R$ 857,593 million and 49 facilities, while Goiás had a GDP of R$ 269,628 million and 36 facilities. In contrast, the states of the Northeast region have a smaller number of enterprises. In 2023, the state of Alagoas recorded a GDP of R$ 76,266 million and 21 operational facilities; Pernambuco, a GDP of R$ 220,814 million and 18 facilities; Paraíba, a GDP of R$ 77,470 million and 5 facilities; and Sergipe, a GDP of R$ 51,861 million and also 5 facilities. Rio Grande do Norte recorded a GDP of R$ 80,181 million and 2 facilities, while Tocantins (GDP of R$ 51,781 million) and Piauí (GDP of R$ 64,028 million) each had only one facility.

In light of this, the states within Brazil's less developed regions in the North and Northeast could become production hubs capable of supplying both labor and local feedstock. This combination would play a dual role: providing services to meet the future demand of the SAF market and helping reduce the disparities between the productive structures of the South/Southeast and the North/Northeast regions (Pochmann & Silva, 2020). It is important to emphasize that the existing disparities between these regions stem from the structure of economic organization and the local development dynamics. Therefore, it is essential to promote higher value-added activities in less developed regions, given that more developed regions tend to attract greater investment (Souza et al., 2022).

5. CONCLUSION

Given the framework of the decarbonization process in the transport sector and the challenges of meeting future demands for raw materials (energy security) in key and carbon-intensive activities, such as aviation, different economies have adopted policies and measures directed toward the sector. Among the strategies to meet the targets established in cooperation agreements, the project for the production of sustainable aviation fuels (SAF) stands out.

Considered an activity that makes intensive use of fossil fuels, it is estimated that by 2050 the transformation of the transportation sector will lead to a reduction of up to 87% in CO_2 emission levels. In Brazil, in 2022, the production of fuels for the aviation sector reached 4.9 million m^3, representing about 5% of the country's total oil-derived fuels. With consolidated experience in the production of biofuels for motor vehicles from the production of ethanol from sugarcane biomass, Brazil shows potential for developing a SAF production industry.

In this context, this study aimed to identify the locations in Brazilian regions with the potential to meet future demands for SAF made using sugarcane bagasse. The analysis was based on an estimate of the need for SAF production in Brazil and the construction of the Location Quotient indicator for biomass production (GW) in each state of the country.

Currently, Brazil is the world's largest producer of sugarcane and its residues. Although activities are predominantly concentrated in the South and Southeast regions, there are also small and medium-sized production chains in the North and Northeast regions. These latter regions, historically marked by intense social and economic disparities in the country, partly as a result of regional economic organization and the local development pattern, have the potential to supply future demand for SAF. In this sense, the development of activities in these economically disadvantaged regions that have the potential to meet future sustainability demands could serve a dual purpose: decarbonizing aviation activities and promoting local development.

With the targets established by the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), it is estimated that, starting in 2027, the sector will undergo a transformation through offset mechanisms (through the acquisition of carbon credits) and a reduction in emission levels via the use of sustainable fuels.

SAF production in Brazil will have a minimum threshold established by domestic legislation, requiring a progressive blend ratio to meet the targets established by the international CORSIA agreement. According to current regulations under discussion in the country, the initial target consists of using 1% renewable sources in fuel composition beginning in 2027, progressively reaching 10% by 2037. Based on this target and considering current production, it is estimated that 49.09 million liters of SAF should be produced domestically in 2027 to supply the aviation sector, which could be obtained from 1.7 million tons of sugarcane, representing 0.25% of the country's available production. For 2037, following CORSIA's targets, sugarcane biomass demand would increase from 460 thousand tons in 2027 to 4.62 million tons in 2037.

In addition to the states that show the highest volume of sugarcane production, such as São Paulo (6,306,548.2 kW), Minas Gerais (1,649,920 kW), Goiás (1,474,068 kW), and Mato Grosso do Sul (1,159,409 kW), the Location Quotient results indicate productive specialization in some states in the Northeast region of Brazil, especially Alagoas (357,462 kW), Pernambuco (317,575 kW), Paraíba (101,500 kW), Rio Grande do Norte (61,000 kW), and Sergipe (59,700 kW).

Thus, from the targets established, significant regional implications may arise starting in 2027. The only states that have the production capacity to fully meet the estimated demand by 2037 are São Paulo and Minas Gerais (Southeast), Paraná (South), and Mato Grosso do Sul (Central-West). In the Northeast, the states with pre-existing capacity to fully meet the estimated demand by 2037 – keeping all else constant – are Alagoas and Pernambuco, but only when considering their combined production.

Some further points should be highlighted: i) although initial production may incur higher costs than traditional fossil fuels already established in the market given their technological maturity, Brazil still has potential to develop production scale directed toward SAF in several regions of the country; ii) considering the need to mitigate greenhouse gas emissions, the creation of this market through norms, certification, and regulation is essential to meet the targets set in international cooperation agreements and to take advantage of the opportunity window this market offers Brazil; and iii) finally, to reduce external technological dependence, it is essential to develop ambitious and stable policies, especially industrial policies capable of promoting a systemic shift through collaboration among different market actors, including industry, research centers, airlines, government, and stakeholders.

In order to meet future global demands for sustainable biofuels, Brazil shows potential to benefit from this boom because of the availability of farmland for the production of sugarcane biomass. In addition, developing the high value-added SAF production chain may serve as a pathway to promote sectoral decarbonization and to mitigate the disparities between regions of the country, especially in the Northeast. However, to fully benefit from the transition of this market, it is essential to develop a domestic industry in locations with available agricultural land for biomass production destined for the sector. Furthermore, medium- and long-term planning is crucial, since the current production dynamics may limit biomass supply for the SAF market and consequently exert upward pressure on prices as well as exacerbate regional inequalities.

References

ALBUQUERQUE, Cristhian *et al.* **Produção de energia renovável por meio de biomassa avícola: o caso do Norte do Paraná**. *Brazilian Applied Science Review*, v. 6, n. 2, p. 731-750, 2022.

AGÊNCIA NACIONAL DE AVIAÇÃO CIVIL (ANAC). *CORSIA:* ***Carbon Offsetting and Reduction Scheme for International Aviation.*** Brasília, DF, 2019. Disponível em: https://www.gov.br/anac/pt-br/assuntos/meio-ambiente/corsia.

AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA (ANEEL). ***SIGA – Sistema de Informações de Geração da ANEEL***. Brasília, DF, 2023. Disponível em: https://www.aneel.gov.br/siga.

AGÊNCIA NACIONAL DO PETRÓLEO, GÁS NATURAL E BIOCOMBUSTÍVEIS (ANP). ***Anuário estatístico brasileiro do petróleo, gás natural e biocombustíveis 2023***. Rio de Janeiro: ANP, 2023. Disponível em: https://www.gov.br/anp/pt-br/centrais-de-conteudo/publicacoes/anuario-estatistico/anuario-estatistico-2023.

BRASIL. Ministério de Minas e Energia. Resolução nº 7, de 20 de abril de 2021. **Institui o Programa Combustível do Futuro, cria o Comitê Técnico Combustível do Futuro e dá outras providências**. *Diário Oficial da União*, Brasília, DF, 27 abr. 2021.

BRASIL. Resolução nº 778, de 5 de abril de 2019. **Estabelece as especificações do querosene de aviação, querosenes de aviação alternativos e do querosene de aviação** [...]. *Diário Oficial da União*, Brasília, DF, n. 67, p. 40, 8 abr. 2019. Disponível em: https://www.in.gov.br/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/70491356/do1-2019-04-08-resolucao-n778-de-5-de-abril-de-2019-70491250.

CORTEZ, Luís Augusto Barbosa *et al.* **PROÁLCOOL 40 anos: universidades e empresas: 40 anos de ciência e tecnologia para o etanol brasileiro**. São Paulo: Blucher, 2016.

DANTAS FILHO, Paulo. ***Análise de custos na geração de energia com bagaço de cana-de-açúcar: um estudo de caso em quatro usinas de São Paulo***. 2019. Dissertação (Mestrado) – Universidade de São Paulo, São Paulo, 2019.

EMPRESA DE PESQUISA ENERGÉTICA (EPE). ***Análise de conjuntura dos biocombustíveis: ano 2020***. Brasília, DF: Ministério de Minas e Energia, 2021.

EMPRESA DE PESQUISA ENERGÉTICA (EPE). ***Balanço energético nacional 2023***. Brasília, DF: Ministério de Minas e Energia, 2023.

GREENPEACE BRASIL. ***Revolução energética: rumo a um Brasil com 100% de energias limpas e renováveis***. Ricardo Baitelo (org.). São Paulo: Greenpeace Brasil, 2016.

HADDAD, Paulo Roberto *et al.* ***Economia regional: teorias e métodos de análise***. Fortaleza: Banco do Nordeste do Brasil, 1989.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE). ***Censo agropecuário 2017.*** Rio de Janeiro: IBGE, 2017.

INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA). **Global renewables outlook: energy transformation 2050**. Abu Dhabi: IRENA, 2020.

INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA). **Reaching zero with renewables: biojet fuels**. Abu Dhabi: IRENA, 2021.

INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA). **World energy transitions outlook 2023: 1.5°C pathway.** Abu Dhabi: IRENA, 2023.

IRENA – International Renewable Energy Agency. (2024). **Sustainable bioenergy potential in Caribbean small island developing states**. Abu Dhabi.

INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA). **Sustainable bioenergy potential in Caribbean small island developing states**. Abu Dhabi: IRENA, 2024.

INTERNATIONAL TRANSPORT FORUM (ITF). **Transport outlook 2021**. Paris: OECD Publishing, 2021.

LEAL, Alan *et al***. Efeitos do crescimento econômico sobre a desigualdade salarial por gênero no Nordeste – Brasil**. *Revista GeoNordeste*, n. 1, p. 151-169, 2021.

MENEZES, Rômulo *et al.* **Biomassa, energia e desenvolvimento na região Nordeste do Brasil: histórico e perspectivas**. *Revista Inovação e Desenvolvimento*, v. 1, n. 9, 2022.

MILANEZ, Artur *et al.* **Biocombustíveis de aviação no Brasil: uma agenda de sustentabilidade.** *Revista do BNDES*, Rio de Janeiro, v. 28, n. 56, p. 361-398, 2021.

MINISTÉRIO DO MEIO AMBIENTE (MMA). ***Conferência das Partes***. Brasília, DF, 2024. Disponível em: https://antigo.mma.gov.br/clima/convencao-das-nacoes-unidas/conferencia-das-partes.html.

ORGANIZAÇÃO DAS NAÇÕES UNIDAS (ONU). ***Nosso futuro comum: comissão mundial sobre meio ambiente e desenvolvimento***. Rio de Janeiro: Fundação Getulio Vargas, 1991.

POCHMANN, Marcio; SILVA, Luciana. **Concentração espacial da produção e desigualdades sociais**. *Revista Brasileira de Estudos Urbanos e Regionais*, v. 22, 2020.

SISTEMA DE ESTIMATIVAS DE EMISSÕES DE GASES DE EFEITO ESTUFA (SEEG). ***Análise das emissões de gases de efeito estufa e suas implicações para as metas climáticas do Brasil***. 2023. Disponível em: https://plataforma.seeg.eco.br/.

SOUZA, Solange *et al.* **Efeitos da segmentação regional nos salários dos trabalhadores do Nordeste e Sudeste do Brasil**. *Interações*, v. 23, n. 4, p. 1051-1067, 2022.

WATSON, M. *et al.* **Sustainable aviation fuel technologies, costs, emissions, policies, and markets: a critical review**. *Journal of Cleaner Production*, v. 449, 2024.

José Ricardo de Santana. *Doutor em Economia de Empresas pela Fundação Getulio Vargas, São Paulo, Brasil. Departamento de Economia, Universidade Federal de Sergipe, Sergipe, Brasil. Professor do Programa de Pós-Graduação em Economia. E-mail: jrsantanaufs@gmail.com*

Lindomayara França Ferreira. *Doutora em Economia pela Universidade Federal Juiz de Fora, Minas Gerais, Brasil. Departamento de Engenharia da Faculdade de Tiradentes, Sergipe, Brasil. Pós-doutorado em Economia. E-mail: lindomayara@hotmail.com*

Marcelo da Costa Mendonça. *Doutorado em Química e Biotecnologia pela Universidade Federal de Alagoas, Alagoas, Brasil. Departamento de Engenharia da Faculdade de Tiradentes, Sergipe, Brasil. Professor do Programa de Pós-Graduação em Biotecnologia Industrial.*
E-mail: marcelo_costa@unit.br

Claudio Dariva. *Doutorado em Engenharia Química pela Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brasil. Departamento de Engenharia da Faculdade de Tiradentes, Sergipe, Brasil. Professor do Programa de Pós-Graduação em Engenharia de Processos.*
E-mail: claudio.dariva@gmail.com

Submetido em: 08/09/2024 **Aprovado em: 05/05/2026**

CONTRIBUIÇÃO DE CADA AUTOR

Conceituação: José Ricardo de Santana e Lindomayara França Ferreira
Curadoria de Dados: José Ricardo de Santana e Lindomayara França Ferreira
Análise Formal: José Ricardo de Santana e Lindomayara França Ferreira
Obtenção de Financiamento: Não se aplica
Investigação/Pesquisa: José Ricardo de Santana e Lindomayara França Ferreira
Metodologia: José Ricardo de Santana e Lindomayara França Ferreira
Administração do Projeto: José Ricardo de Santana
Recursos: Não se aplica
Software: Não se aplica
Supervisão/orientação: José Ricardo de Santana

Validação (Validation): José Ricardo de Santana, Lindomayara França Ferreira, Marcelo da Costa Mendonça, Claudio Dariva
Visualização (Visualization): José Ricardo de Santana, Lindomayara França Ferreira, Marcelo da Costa Mendonça, Claudio Dariva
Escrita – Primeira Redação: José Ricardo de Santana e Lindomayara França Ferreira
Escrita – Revisão e Edição: José Ricardo de Santana, Lindomayara França Ferreira, Marcelo da Costa Mendonça, Claudio Dariva
Fontes de financiamento: Não se aplica