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THE EVOLUTION OF BRAZIL'S SUGARENERGY SECTOR IN THE POST FLEX-FUEL ERA (2003-2025): DRIVERS AND PROSPECTS

Natalia Guzella Perin[1]
Wellington Francisco Bescorovaine[2]
Alondra Aurelia Palma Fernández[3]
Pery Francisco Assis Shikida[4]

Abstract: This article analyzes the structural transformations of the sugar-energy sector between 2003 and 2025. The objective is to identify the economic and institutional factors that have shaped the trajectory of the sector following the introduction of flex-fuel vehicles. The methodology adopts a qualitative and explanatory approach, using the historical-deductive method and secondary data from CONAB, ANFAVEA, and UNICA. Statistical analysis and the organization of time series were conducted using the R programming language. The results show that flex-fuel technology has stabilized at levels above 80% of national vehicle registrations, ensuring demand security and raising the production floor of ethanol to more than 30 billion liters annually. A geographic reconfiguration toward the Center-West region is observed, driven by the rise of corn as a complementary feedstock, which has reduced industrial idle capacity and generated relevant co-products for animal nutrition. The analysis highlights the resilience of biofuel supply in the face of fluctuations in the new vehicle market and the volatility of international sugar prices. It is concluded that regulatory frameworks such as RenovaBio have consolidated renewable fuel as a strategic asset in the global climate agenda.

Keywords: Agroindustry; biofuels; RenovaBio; food security; decarbonization.

A EVOLUÇÃO DO SETOR SUCROENERGÉTICO NO BRASIL PÓS FLEX-FUEL (2003-2025): CONDICIONANTES E PERSPECTIVAS

Resumo: *Este artigo analisa as transformações estruturais do setor sucroenergético entre 2003 e 2025. O objetivo é identificar os fatores econômicos e institucionais que moldaram a trajetória da atividade após a introdução dos veículos flex-fuel. A metodologia adota abordagem qualitativa e explicativa, com o uso do método histórico-dedutivo e levantamento de dados secundários da CONAB, ANFAVEA e UNICA. O tratamento estatístico e a organização das séries históricas ocorreram na linguagem R. Os resultados demonstram que a tecnologia de combustíveis flexíveis se estabilizou em patamares superiores a 80% dos licenciamentos nacionais, o que garantiu segurança de demanda e elevou o piso produtivo de etanol para mais de 30 bilhões de litros anuais. Observa-se uma reconfiguração geográfica em direção ao Centro-Oeste, impulsionada pela ascensão do milho como matéria-prima complementar, o que reduziu a ociosidade industrial e gerou coprodutos relevantes para a nutrição animal. A análise evidencia a resiliência da oferta de biocombustíveis frente às oscilações no mercado de veículos novos e à volatilidade dos preços internacionais do açúcar. Conclui-se que marcos regulatórios como o RenovaBio consolidaram o combustível renovável como ativo estratégico na agenda climática global.*

Palavras-chave: *Agroindústria; biocombustíveis; Renovabio; segurança alimentar; descarbonização.*

[1] PhD candidate in Regional Development and Agribusiness at PGDRA, Universidade Estadual do Oeste do Paraná (UNIOESTE). Capes scholarship holder. ORCID: https://orcid.org/0000-0002-4174-8846. Lattes: http://lattes.cnpq.br/4666751710471342. E-mail: nataliagp@live.com.
[2] PhD candidate in Regional Development and Agribusiness at PGDRA, Universidade Estadual do Oeste do Paraná (UNIOESTE). Capes scholarship holder. ORCID: https://orcid.org/0000-0002-8569-742X. Lattes: http://lattes.cnpq.br/1787848869594549. E-mail: wellingtonbescorovaine@gmail.com.
[3] PhD candidate in Regional Development and Agribusiness at PGDRA, Universidade Estadual do Oeste do Paraná (UNIOESTE). Capes scholarship holder. ORCID: https://orcid.org/0009-0006-8307-0283. Lattes: http://lattes.cnpq.br/6821089582714656. E-mail: alondrapalma@gmail.com.
[4] Postdoctoral researcher at Fundação Getúlio Vargas (FGV-SP), PhD in Applied Economics and Master's in Agricultural Economics from Escola Superior de Agricultura "Luiz de Queiroz"/Universidade de São Paulo, Economist from Universidade Federal de Minas Gerais. CNPq Research Productivity scholarship holder since 2003. ORCID: https://orcid.org/0000-0001-9621-1520. Lattes: http://lattes.cnpq.br/1740467499247374. E-mail: pery.shikida@unioeste.br

1 Introduction

The Brazilian sugarenergy sector occupies a strategic position in the global sugar and biofuels market. The country has established itself as the world's largest sugar exporter and one of the leading ethanol producers, driven by favorable natural conditions, high agricultural productivity, and technological advances. Sugarcane production is the foundation of this agroindustrial system, which integrates agricultural, industrial, and energy activities. It represents a strong performance in the national economy and in the international trade of ethanol, sugar, and energy (Neves; Conejero, 2007; Vian, 2015; Shikida, 2025).

Beyond its economic importance, sugarcane has played a central role in the Brazilian energy matrix since the implementation of the National Alcohol Program (Proálcool) in 1975, created in response to the international oil crisis and with the aim of reducing dependence on imported fossil fuels. The Program drove the expansion of fuel ethanol production and fostered the technological development of the sugarenergy chain, laying the foundations for Brazil's consolidation as the world leader in sugarcane ethanol production (Tonelli *et al*., 2025).

The introduction of flex-fuel vehicles in 2003 boosted domestic ethanol consumption and strengthened the integration between agriculture, industry, and the energy sector. In addition to the technological expansion driven by *flex* vehicles, Brazil is experiencing a new bioenergy revolution with the rapid growth of corn ethanol. This new productive integration has allowed distilleries to operate year-round and introduced the generation of high-value co-products for animal nutrition (Neves, 2021; Vidal, 2024).

However, this vigorous expansion of energy crops has reignited the global debate on food security, often framed around the premise of competition between food and fuel. Faced with this controversy, the Latin American experience, especially the paradigms adopted by Brazil, offers empirical evidence that deconstructs this dichotomy (Justus *et al.*, 2025).

In this sense, this article analyzes how the Brazilian sugarenergy sector evolved in the post flex-fuel period (2003-2025) and what factors conditioned this trajectory. It examines the main structural transformations and the economic and institutional factors that influenced them. It also discusses the challenges related to the diversification of biofuel production and the implications of the food *versus* energy debate for food security.

To achieve these objectives, the study examines the trajectory of ethanol production, sugarcane production, and the allocation of feedstock between sugar and ethanol between 2003 and 2025. The article is organized into five sections: this introduction, followed by a literature review on the sugarenergy sector and the debate on biofuels and food security. The third section describes the methods used, while the fourth section comprises the results and discussion. The

fifth section presents the concluding remarks.

2 Theoretical framework

The Brazilian sugarenergy sector, already established as a global benchmark through sugarcane cultivation, has undergone an evolution toward the diversification and optimization of its production base. To overcome the challenge of seasonality and industrial idle capacity during the sugarcane off-season, the sector sought, starting in 2012 in Mato Grosso, strategic integration with corn as a complementary feedstock (Freitas; Miura, 2018).

This trajectory enabled the transition from the traditional model to the coexistence of *flex* plants (which process both sugarcane and corn) and *full* units (dedicated exclusively to grain), taking advantage of production surpluses and already installed infrastructure. Today, this evolution is expanding into new frontiers, such as the Northeast, and is supported by regulatory frameworks such as RenovaBio, consolidating corn ethanol as an ally for energy security and the decarbonization of this matrix (Neves, 2021; Milanez *et al*., 2014; Vidal, 2024).

In Brazil, ethanol and flex-fuel engines play a unique role in the energy transition, functioning both as a transitional technology and as a competitive differentiator that shapes the pace of adoption of purely electric vehicles. Unlike many developed countries seeking an abrupt shift to battery electric vehicles, Brazil is betting on *flex* hybrid vehicles as a less abrupt transition, since ethanol is considered a clean and renewable energy source (Souza; Hiroi, 2021; Vidal, 2024).

Thus, in the Brazilian case, the biofuel production chain and flex-fuel technology create a scenario in which the immediate need for electric cars is not perceived in the same way as in Europe or Asia. While electric vehicles still face obstacles such as high prices and a lack of charging infrastructure, *flex* cars are affordable and benefit from an already installed fuel-station distribution network. For this reason, *flex* engines and ethanol allow Brazil to carry out a gradual energy transition, using a renewable source already integrated into its economy to complement electrification, rather than relying exclusively on the total replacement of the fleet with electric vehicles (Gonçalves, 2017).

From this perspective, some authors argue that the expansion of bioenergy could generate competition for land use and strategic productive resources. However, recent research suggests that this relationship does not necessarily imply direct competition between the two uses (Justus *et al*., 2025). In the Brazilian case, high agricultural productivity, the availability of degraded pastures suitable for recovery, and the integration of production chains have allowed the expansion of the bioenergy sector without compromising food production (União da Indústria de Cana-de-Açúcar e Bioenergia — UNICA, 2025; Companhia Nacional de Abastecimento —

CONAB, 2025a). Furthermore, the increase in corn ethanol production has generated by-products of high nutritional value, widely used in animal nutrition, which strengthens the link between the energy and food systems (CONAB, 2025a; União Nacional do Etanol de Milho — UNEM, 2026).

Given this dynamic, the development of the Brazilian sugarenergy sector has been interpreted by the international literature as a practical and successful example of an integrated, circular bioeconomy (Sáez-Navarrete, 2025).

3 Materials and Methods

This research adopts a qualitative and explanatory approach, using the historical-deductive method to analyze the evolution of Brazil's sugarenergy sector and its socio-spatial and economic implications. Qualitative research encompasses phenomena beyond numerical variables, covering regulatory changes, business strategies, and the reconfiguration of the productive territory (De Abreu Santana; Narciso, 2025).

The data collection used secondary sources from sector-reference institutions covering 2003 to 2025. Agricultural and industrial production data come from CONAB. Historical series on vehicle registrations and the technological evolution of the fleet were drawn from the Associação Nacional dos Fabricantes de Veículos Automotores (ANFAVEA). UNICA was also consulted to obtain consumption and regional crushing indicators.

The statistical treatment, the systematization of supply and demand variables, and the correlation of historical series were carried out using the *R* programming language (version 4.5.2) in the RStudio environment. The ggplot2 package was used to create the visual evidence and analyze market dynamics. This tool allowed the overlay of time series on dual axes in order to assess the interdependence between ethanol production and the consolidation of flex-fuel technology. In addition, consumption indicators and crushing variables underwent a complementary electronic tabulation process. This information was integrated into the main database to enable a holistic understanding of the behavior of the circulating fleet and the national energy supply.

To support the discussions on food security, the study incorporates technical documents prepared by international organizations, notably the Food and Agriculture Organization of the United Nations (FAO) and the Organisation for Economic Co-operation and Development (OECD), together with reports from research centers specializing in bioeconomy, agricultural markets, and energy systems.

The theoretical framework provides the structure for examining the tensions between energy production and the availability of land for food cultivation. The aim is to identify

potential socio-spatial conflicts and assess how agricultural productivity can mitigate these risks. The results of the computational processing in *R* were directly compared against the literature. This process made it possible to validate the hypotheses about the sector and analyze the impacts of bi-fuel technology as a sustainable transition solution for the national transportation matrix.

4 Results and Discussion

To improve the understanding of the results, this topic was divided into four parts:

4.1 The Flex-Fuel Era and Consumption Dynamics (2003-2025)

Proálcool, created by Decree No. 76.593/1975, is an important milestone in Brazil's energy and industrial policy. It emerged in response to instabilities in the external energy market (Tonelli *et al*., 2025). The Program was created mainly to reduce the impacts of the oil crises of the 1970s and balance the trade balance. Its trajectory was marked by strong state support and periods of structural fragility. In addition to seeking import substitution, this initial effort structured the basis for a productive and technological infrastructure that would allow Brazil to lead biofuel production.

The initial expansion phase of Proálcool, divided into moderate growth (1975-1979) and accelerated growth (1980-1985), consolidated ethanol as a viable alternative to fossil derivatives. In 1985, at the peak of this stage, the licensing of vehicles running exclusively on hydrous ethanol reached a historic record of 92.2% of national sales (ANFAVEA, 2024). This success was the result of collaboration between the State, the automotive industry, and the sugarenergy sector, which provided a secure environment for large-scale investment in both agriculture and industry (Tonin; Tonin, 2014).

The consolidation of this infrastructure was not limited to domestic supply but positioned the sector as a macroeconomic pillar of global importance. Data from UNICA (2025) reveal that the gross value moved by the sugarenergy sector exceeded US$ 100 billion, with a direct contribution to Gross Domestic Product of US$ 40 billion. Brazil's economic strengthening boosted its presence in foreign markets and resulted in ethanol exports exceeding 2.5 billion liters, generating US$ 1.53 billion in foreign exchange. The biofuel became consolidated as an item in Brazil's trade agenda (UNICA, 2025).

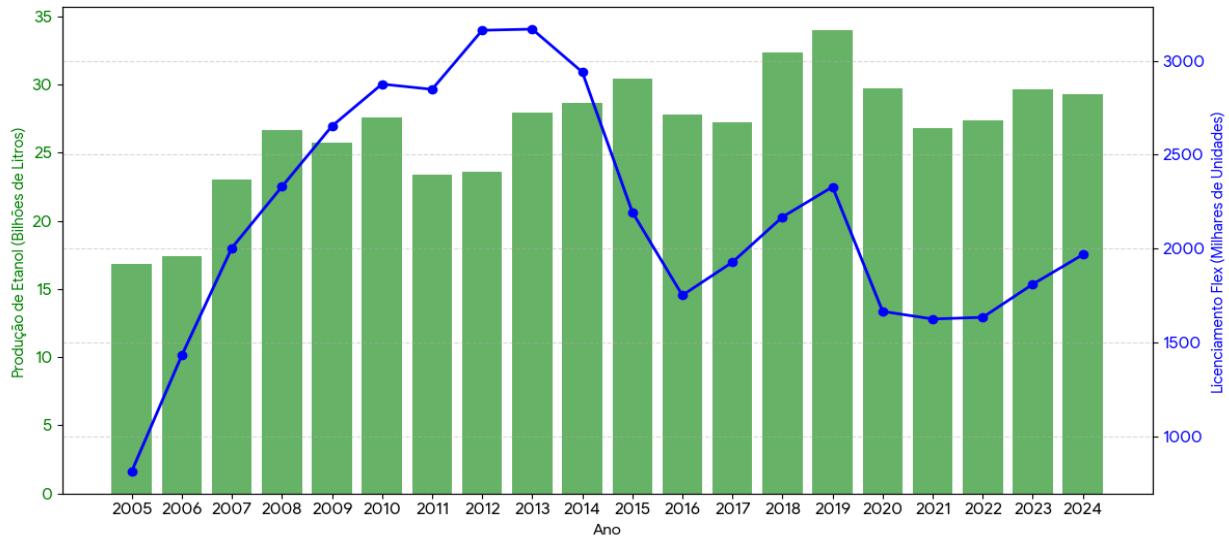
The 1990s, however, brought a severe crisis of confidence to the sector, characterized by deregulation and fragmentation of interests (Shikida, 2014). Economic liberalization, combined with rising sugar prices abroad and falling international oil prices, caused episodes of hydrous ethanol shortages (Szmrecsányi, 2002). In 1995, licensing of ethanol-powered vehicles plummeted to just 2.5%, revealing the fragility of a model that lacked a flexible vehicle fleet

capable of adjusting to fluctuations in the prices and supply of different fuels (ANFAVEA, 2024). This situation forced the sector to seek new strategies to increase efficiency and reduce dependence on government subsidies.

The introduction of flex-fuel technology in 2003 marked a turning point in the trajectory of the sugarcane agroindustry and redefined its future. This innovation changed the logic of consumption by shifting to the vehicle's driver the decision of which fuel to use at the time of refueling, reducing the demand risk that had plagued the sector in the 1990s (Tonelli *et al.*, 2025). The flexibility of this technology allowed ethanol to act as a price buffer against gasoline, rehabilitated the renewable fuel in the domestic market, and strengthened energy security regardless of oil price fluctuations.

The maturity of the technology is evidenced by the fact that 81.6% of the light-vehicle fleet in Brazil is made up of *flex* models, which ensures sustainable demand for the sugarenergy sector (ANFAVEA, 2024). It is possible to verify the consolidation of flex-fuel technology as the main driver sustaining the sector (Figure 1).

Figure 1 – Evolution of the sugarenergy sector: ethanol supply *vs.* adoption of *flex* technology (2005-2024)



Source: Prepared by the authors based on data compiled from ANFAVEA (2024) and CONAB (2025a).

Figure 1 shows that the share of bi-fuel vehicles in licensing grew markedly, stabilizing at high levels after 2010. This change in the fleet profile brought demand security and contributed to national ethanol production raising its production floor from 17 billion to levels exceeding 30 billion liters per year. Thus, the relationship between the technology-adoption line and the fuel-supply bars reinforces the thesis of the sector's rehabilitation in the 21st century.

The demand security established by the bi-fuel fleet created the environment needed for the productive evolution of the sugarenergy sector. This scenario of predictability allowed the

activity to transcend simple market recovery and begin a cycle of structural expansion. The movement was not limited to increased volumes but also caused profound changes in the spatial organization of the agroindustry.

Market stability drove the geographic decentralization of production, expanding the traditional frontiers toward the Center-West region. In this new scenario, corn ethanol in states such as Mato Grosso and Goiás gained prominence, representing about 20% of the country's total ethanol supply. This expansion enabled continuous production throughout the year, including during the sugarcane off-season (CONAB, 2025b).

The integration of corn into ethanol production gave rise to a new industrial model known as '*full*' and '*flex*' plants. This integration, according to CONAB (2025b), allowed the sector to overcome industrial idle capacity during the sugarcane off-season and ensured a more stable and predictable supply of hydrous ethanol to the market. In addition to fuel production, this dynamic generates high value-added co-products, such as distillers' grains, which serve as a protein input for beef and dairy cattle farming. This reinforces the integration between the energy and animal-protein production chains in agriculture (CONAB, 2025b).

Between 2003 and 2025, modern regulatory frameworks, such as RenovaBio (Law No. 13.576/2017), shaped the evolution of consumption and production. This public policy integrated the sector into the decarbonization credit market (CBIOs) by recognizing the environmental efficiency and low carbon footprint of domestic production. It is estimated that, between 2003 and 2023, the use of ethanol avoided the emission of 660 million tons of CO_2 (UNICA, 2025; Shikida, 2025). As a result, ethanol is no longer seen merely as an economic alternative but has come to be regarded as a strategic environmental asset on the global climate agenda.

RenovaBio, unlike the direct subsidies that marked the early days of Proálcool, operates through market mechanisms and efficiency certification. The policy sets annual decarbonization targets for fuel distributors, which are met by purchasing CBIOs issued by biofuel producers. Each CBIO represents one ton of CO_2 avoided relative to the equivalent fossil fuel. This regulatory arrangement not only encourages production expansion but also rewards the energy and environmental efficiency of the plants. The amount of credits generated is directly linked to the efficiency score obtained throughout the production process, from the field to the industrial stage (Brasil, 2017; Shikida, 2025).

In Brazil, empirical evidence has refuted the alleged competition between "food *versus* fuel," which was previously a point of controversy alongside productive growth. Recent studies indicate that high agricultural productivity and the availability of degraded land for recovery enable the harmonious coexistence of both types of production without compromising national

food security (Justus *et al*., 2025). Furthermore, the integration between livestock farming and sugarcane, combined with the use of by-products such as vinasse and bagasse for bioelectricity generation, strengthens the circular character of the sector's economy and raises the sustainability level of the agroindustry.

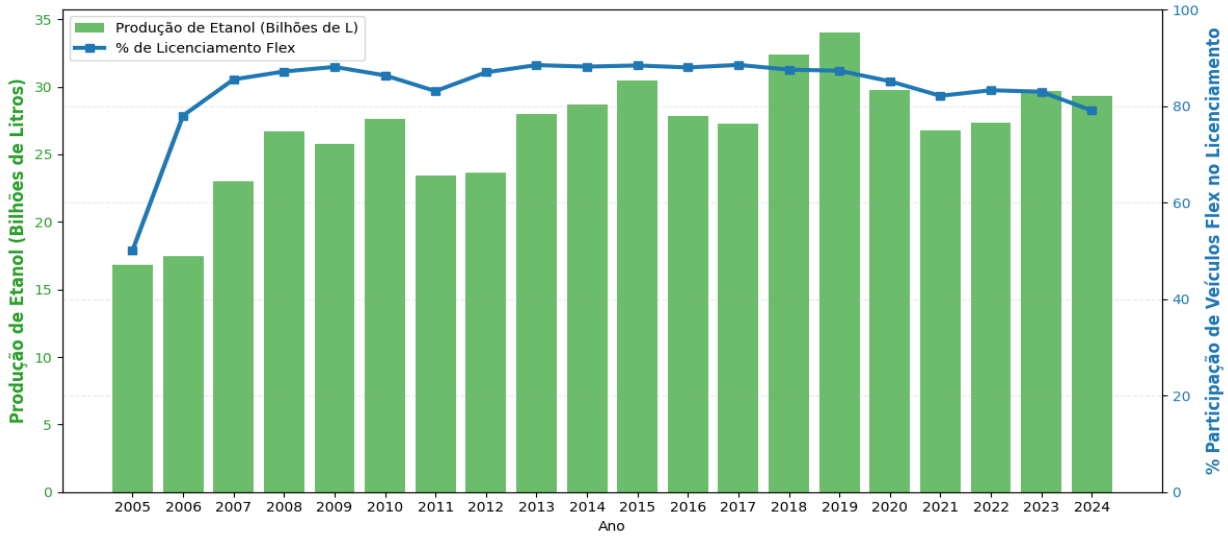
Land-occupation data reinforce the empirical basis for the coexistence between food and energy crops. According to UNICA (2025), only 1.2% of Brazilian territory is used for sugarcane cultivation, and of that total, 0.9% is allocated to ethanol production. This proportion, which allows for the expansion of production projected at 678.7 million tons (2024/25 harvest) is mainly due to productivity gains and the conversion of degraded pastureland, rather than to a reduction in grain acreage. This reinforces the sustainability thesis of the Brazilian decarbonization model (Shikida, 2025; CONAB, 2025a).

Currently, global vehicle electrification represents a challenge for consumption dynamics. However, Brazil is charting its own technological path. The national strategy prioritizes hybridization, which combines electric motors with the use of biofuels, making it possible to take advantage of the already extensive distribution infrastructure (Shikida, 2025). With an estimated production of 678.7 million tons of sugarcane for the 2024/25 harvest (CONAB, 2025a), the country demonstrates that the legacy of Proálcool has evolved into a relevant energy matrix. Ethanol emerges as the pillar for an energy transition that is both economically viable and environmentally responsible.

Upon completing five decades, the sugarenergy sector reveals its role as a buffer against macroeconomic crises, going beyond simple import substitution. As pointed out by Ueki (2025) and Shikida (2025), the absence of ethanol from the current energy matrix would leave the country vulnerable to the volatility of international oil prices, with direct impacts on inflation and GDP. The transition from flex-fuel models to hybrids is not merely a technical decision but an affirmation of a model of energy sovereignty and decarbonization that can be used as a global reference. By grounding itself in the productive integration of sugarcane, corn, and the regulatory rigor of RenovaBio, the sector closes this cycle as the basis for Brazil's competitive insertion into the low-carbon economy.

Figure 2 allows for a comparison between the absolute volume of *flex* vehicle licensing and the response of the sugarenergy sector.

Figure 2 – Evolution of the sugarenergy sector: ethanol production *vs. flex* vehicles in units (2005-2024)



Source: Prepared by the authors based on data compiled from ANFAVEA (2024) and CONAB (2026).

It is observed that, even in the face of economic downturns that affected new car sales in specific periods, ethanol production maintained resilient trajectories. This behavior indicates that the sector has structured itself to serve not only the market for brand-new vehicles but also the accumulated circulating fleet, which minimizes the risks of industrial idleness. Figure 2 reinforces ethanol's role as a strategic asset and crisis buffer, while also supporting the viability of hybridization in the face of pure electrification.

The new National Plan on Climate Change (Plano Clima), with an implementation period between 2024 and 2035, also marks a decisive moment in Brazilian policy for the country to fully meet its Paris Agreement targets. The document aims to guide Brazil on its path toward a net-zero greenhouse-gas-emissions economy by 2050. In other words, the Plano Clima should directly influence the dynamics of the Brazilian sugarenergy sector by guiding the national decarbonization strategy. In the transportation sector, the Plan tends to combine different technological routes for emission reduction, including the expansion of biofuels, especially ethanol (Brasil, 2026).

4.2 Geographic reconfiguration of sugarcane production and the rise of corn

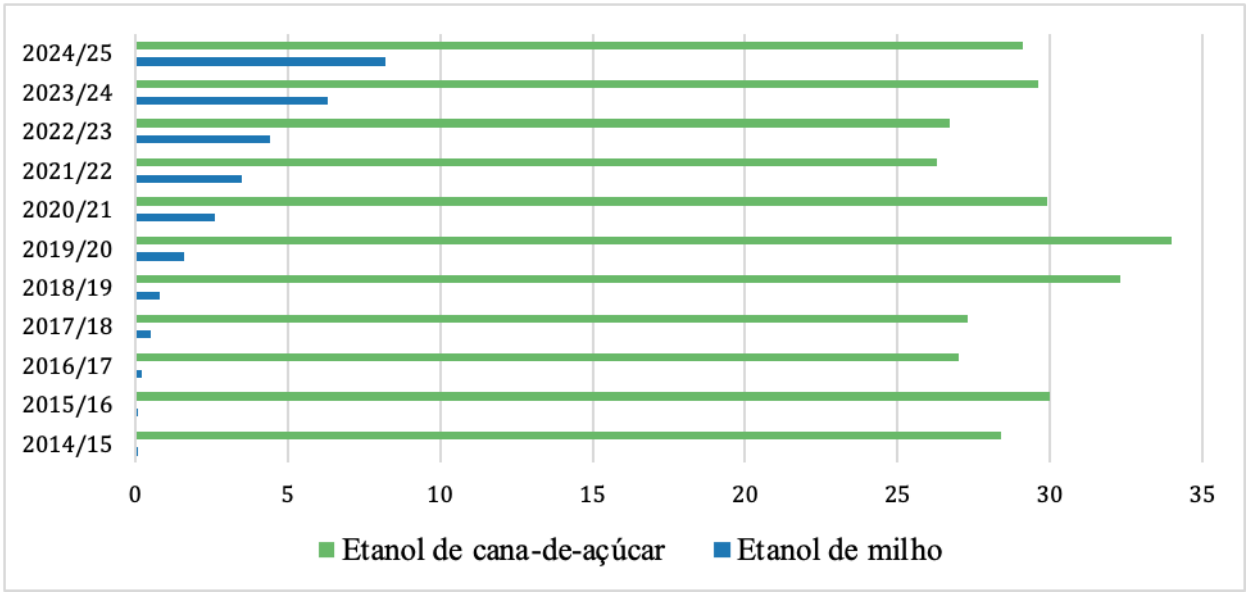
The global energy transition has expanded the role of renewable sources, among which bioenergy stands out as an alternative for reducing emissions in the transportation sector. In this context, Latin America presents favorable conditions for the expansion of this segment, enabling the evolution of sugarenergy plants into integrated biorefineries capable of producing biofuels, bioelectricity, and other bioproducts. Brazil holds a prominent position in this process, supported by its extensive sugarcane ethanol production, the spread of flex-fuel vehicles, and the recent

expansion of corn ethanol (Montabone, 2026).

A survey conducted in 2014 by a team from the Banco Nacional de Desenvolvimento Econômico e Social (BNDES) found that, up to that date, there were only two small-scale plants in Brazil capable of processing both corn and sugarcane (Milanez *et al*., 2014). Brazilian corn ethanol production began in 2012, but around ten years ago, ethanol production from corn in Brazil still seemed like a distant scenario. The subject was treated as an option to be considered, and in few locations, with the exception of Mato Grosso, due to the surplus corn production (Bortoletto; Alcarde, 2015).

In less than a decade, the corn ethanol industry came to play a relevant role in the expansion of biofuels in Brazil, in addition to generating impacts on the animal-protein chain and adding value to agricultural production (Figure 3). In 2026 the country ranks as the world's third-largest corn producer, behind only the United States and China. Over the past ten years, Brazilian production has grown by 40%. Thus, the corn ethanol industry emerges as an alternative for making use of part of the production surpluses, channeling them toward the production of biofuels and co-products such as dried distillers' grains (DDG) and dried distillers' grains with solubles (DDGS) for animal nutrition (UNEM, 2026).

Figure 3 – Ethanol production in Brazil between the 2014/15 and 2024/25 harvests



Source: Prepared by the authors based on data compiled from UNICA (2025).

It is observed that sugarcane ethanol remains the main production source throughout the entire period analyzed, with volumes ranging approximately between 27 and 34 billion liters. The peak of the series occurred in the 2019/20 harvest, followed by a slight decline in subsequent harvests and a later partial recovery. The chart also shows the rapid growth of corn ethanol, whose production was practically non-existent in the early harvests of the series and

began to show significant expansion from the second half of the 2010s onward. This growth becomes more evident from the 2020/21 harvest onward, reflecting the consolidation of new biorefineries, especially in the Center-West region.

Currently, 27 biorefineries are in operation in the country, while 16 projects have construction authorization and another 14 units are planned. Data from the Ministério do Desenvolvimento, Indústria, Comércio e Serviços (MDIC), compiled by the União Nacional do Etanol de Milho, indicate exports of 879,358.40 tons of DDG/DDGS for animal feed, sent to 25 markets a volume 9.77% higher than the 801,101.27 tons recorded in 2024, with cumulative growth of 4.19% (UNEM, 2026).

Another recent milestone was the start of DDG/DDGS exports to China, one of the largest global markets for animal nutrition, previously dominated by North American suppliers. The opening of this market resulted from institutional coordination involving the Ministério da Agricultura e Pecuária, the Ministério das Relações Exteriores, UNEM, and the Agência Brasileira de Promoção de Exportações e Investimentos, which enabled phytosanitary protocols and the accreditation of Brazilian industrial plants for export (UNEM, 2026).

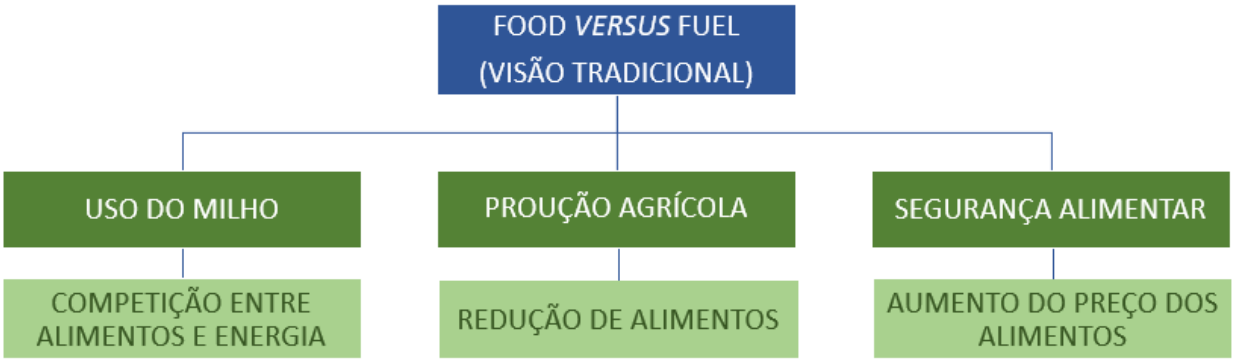
Regarding sustainability, according to Goldemberg (2017), ethanol produced from sugarcane is a practically renewable fuel, with a highly positive energy production balance, since the energy consumed to produce it is almost entirely offset, unlike corn ethanol production, in which the energy used in production comes from other sources, such as coal or wood burning.

Despite the advance in production, corn ethanol still represents a smaller share of total production compared to sugarcane ethanol. However, its upward trajectory indicates a process of diversification of the feedstocks used in biofuel production in Brazil, denoting the expansion of national ethanol supply and the integration between the grain agricultural chains and the sugarenergy sector.

4.3 Biofuels, land use, and the food *versus* energy debate

The debate known as “food *versus* fuel” (Figure 4) attributes pressure on agricultural prices and the potential risk of food scarcity to the expansion of biofuels. According to this perspective, increased demand for agricultural feedstocks for energy production could create direct competition with food production, putting pressure on agricultural markets and compromising global food security. This argument gained strength, particularly after the food crises of the late 2000s, when several studies highlighted the potential impacts of biofuel expansion on international commodity prices (Searchinger *et al*., 2008).

Figure 4 – Logic of the traditional view of the food *versus* energy debate



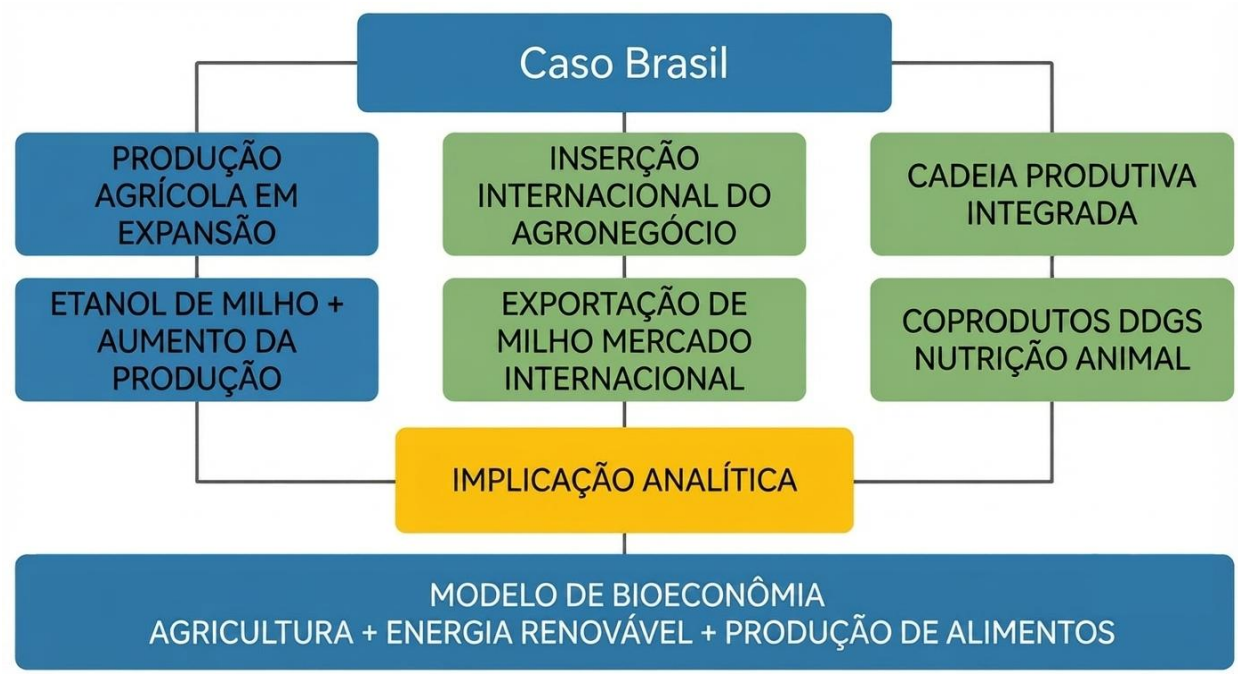
Source: Prepared by the authors based on Searchinger *et al*. (2008)

However, recent empirical evidence has shown that the causes of global food insecurity are primarily linked to exogenous macroeconomic shocks, such as economic crises, geopolitical conflicts, and disruptions in global supply chains factors that directly affect people's purchasing power. The analysis of this dilemma finds institutional support in global projections: OECD and FAO simulations reveal that a scenario of a 20% reduction in global fertilizer supply could raise the food price index by up to 13% in just two years (OECD/FAO, 2025).

Furthermore, analyses by the Inter-American Development Bank (IDB, 2025) confirm that per capita GDP growth has an elasticity of -1 in relation to malnutrition, while inflation directly worsens the food crisis (elasticity of 0.6). According to the Economic Commission for Latin America and the Caribbean — ECLAC (2021), these disruptions generate a deep distributive regression, exacerbating socioeconomic inequality factors that are entirely independent of bioenergy production.

In this context, the Brazilian agroindustrial model (Figure 5) presents a paradigm that empirically refutes direct competition between food and fuel. The rapid expansion of ethanol production, heavily concentrated in the Center-West (such as Mato Grosso and Goiás), does not displace areas of food production for human consumption, since it is based on second-crop ("safrinha") cultivation. This system allows for the intensive use of natural resources, cultivating the land sequentially (for example, planting corn right after the soybean harvest) without the need to expand the cultivated area (Cortez; Salles-Filho; Sbardella, 2023). This harmonious coexistence is further corroborated by Justus *et al*. (2025), who point out that sugarcane occupies only 1.2% of national territory, expanding strategically over degraded pastures, without causing harm to vulnerable populations.

Figure 5 – Model of productive integration of corn in the Brazilian bioeconomy



Source: Prepared by the authors based on Cortez; Salles-Filho; Sbardella (2023) and UNEM (2026).

Goldemberg (2017) states that the notion that biomass use affects food production is mistaken, particularly with regard to ethanol production, framing the situation as a false problem, because there are ample areas available for the expansion of crops that are converted into ethanol, such as sugarcane and corn.

Far from depleting the resources of the food system, and contrary to the traditional logic that associates biofuels with scarcity, the industrial processing of corn ethanol generates significant volumes of by-products (DDG/DDGS). These inputs, rich in protein and fiber, are used in the animal nutrition market. According to MDIC data compiled by UNEM, the country exported 879.4 thousand tons of this product to 25 markets in 2025, a volume 9.77% higher than the 801.1 thousand tons recorded in 2024 (UNEM, 2026).

The introduction of these by-products into ruminant feed drives an intensification effect in livestock farming, which historically occupies vast tracts of land with low animal density. By providing a low-cost concentrated feed, such as DDG, producers can increase the number of animals per hectare. In practice, this increase in animal density leads to the release of thousands of hectares of degraded pastures for grain cultivation or reforestation, demonstrating that the model reverses deforestation and boosts food production (Cortez; Salles-Filho; Sbardella, 2023).

In addition to corn integration, innovations with non-traditional crops and the use of Alcohol-to-Jet (ATJ) technology further reduce competition for fertile land. A paradigmatic example reported by FAO (Hilbert, 2024) is the cultivation of macaúba palm in Brazil, a native

species grown on degraded pastures under a “zero waste” approach. The pulp of the macaúba palm produces protein-rich meal for both human and animal consumption, which simultaneously enables the production of sustainable aviation fuel (SAF), thus providing a circular bioeconomy model.

This paradigm shift extends to other Latin American dynamics. In Peru, studies on public-policy formulation, documented by ECLAC, indicate the absence of significant price vulnerability, since the inputs used in bioenergy have historically been imported, allowing for diversification of the energy matrix without compromising domestic consumption. Econometric analyses based on the Granger causality test, applied in Colombia, indicate that the evolution of the biofuel industry does not causally affect commodity prices (Sánchez Fernández, 2015).

The Colombian strategy structurally redirects sugar and palm-oil export surpluses toward bioenergy, prioritizing and fully guaranteeing the supply of the domestic market. Therefore, a joint analysis of Latin American trajectories makes it possible to deconstruct the central premise of the food-versus-fuel debate. It becomes clear that the threat to food security is not an inherent consequence of bioenergy production but rather a variable that depends on macroeconomic vulnerabilities and on the technological and institutional decisions adopted by each country.

4.4 Future prospects and challenges

Over the past few decades, the expansion of biofuel production and consumption has been driven by public policies aimed at three main objectives: reducing CO_2 emissions, decreasing dependence on imported fossil fuels, and creating new demand opportunities for agricultural crops used as energy feedstock. These policies contributed to consolidating the global biofuels market and stimulated productive investments and technological advances across various agroenergy chains (Brasil, 2026).

For the next decade, although these factors remain relevant in the energy and environmental debate, prospects indicate a more moderate expansion in demand for biofuels. This scenario is associated with a slower pace of government incentives compared to those observed in the sector’s early stages, and with the growing spread of alternative transport technologies, especially electric and hybrid vehicles, which are more efficient at reducing greenhouse-gas emissions. At the same time, gasoline consumption is projected to decline in major ethanol-consuming markets, such as the United States and the European Union, which tends to limit the growth of biofuel demand (OECD-FAO, 2020).

An increase in the share of biofuels in global sugarcane consumption is projected, potentially reaching about 25% by the end of the decade, compared to approximately 23% in the base period (OECD-FAO, 2020). According to the Empresa de Pesquisa Energética (EPE, 2025),

demand for ethanol is expected to grow through 2029, with a production increase of 14 billion liters over the same period (Neves, 2021). This growth is associated with the expansion of decarbonization policies in the transportation sector, particularly RenovaBio.

Globally speaking, about 58% of processed sugarcane is projected to be directed toward ethanol production over the next decade. This trend is likely to be sustained by biofuel incentive policies in Brazil. An increase of approximately 8.3 billion liters in global production is also estimated, with significant Brazilian participation, although the evolution of global energy markets remains a factor of uncertainty (OECD-FAO, 2020).

The corn ethanol sector is expected to increase its share. According to UNEM, there is a projected supply of 8 billion liters by 2028, representing 18% of the total ethanol market (Neves, 2021). In geographic terms, in addition to the Center-West, the Northeast is emerging as an expansion area through *flex* biorefineries and the use of grains from the Matopiba and Sealba regions (Vidal, 2024).

Ethanol consumption in Brazil is expected to reach about 39 billion liters in 2029. Recently, Brazilian legislation raised the mandatory blend of anhydrous ethanol in gasoline from 27% to 30% (E30) (Federação Nacional do Comércio de Combustíveis e de Lubrificantes — Fecombustíveis, 2025). By 2029, more than half of total ethanol production is expected to be consumed by high-blend *flex* vehicles, implying an expansion of this fleet. Significant growth in Brazilian ethanol exports is not expected, as production is expected to mainly meet domestic demand (OECD-FAO, 2020). The fleet of *flex* vehicles will continue to grow in Brazil through 2030, with an expected increase of 17 million vehicles. The hybrid vehicle fleet, in turn, is expected to grow in Brazil in the coming years, reaching 1 million vehicles by 2030 (Neves, 2021; Vidal, 2024).

In the sugar market, Brazil is projected to maintain its position as the world's largest producer of this commodity, accounting for about 18% of global production by 2029, and as the leading world producer of sugar and sugarcane ethanol, accounting for about 39% of global sugarcane production over the same period. This implies that about 90% of the world's sugarcane ethanol comes from Brazil (OECD-FAO, 2020).

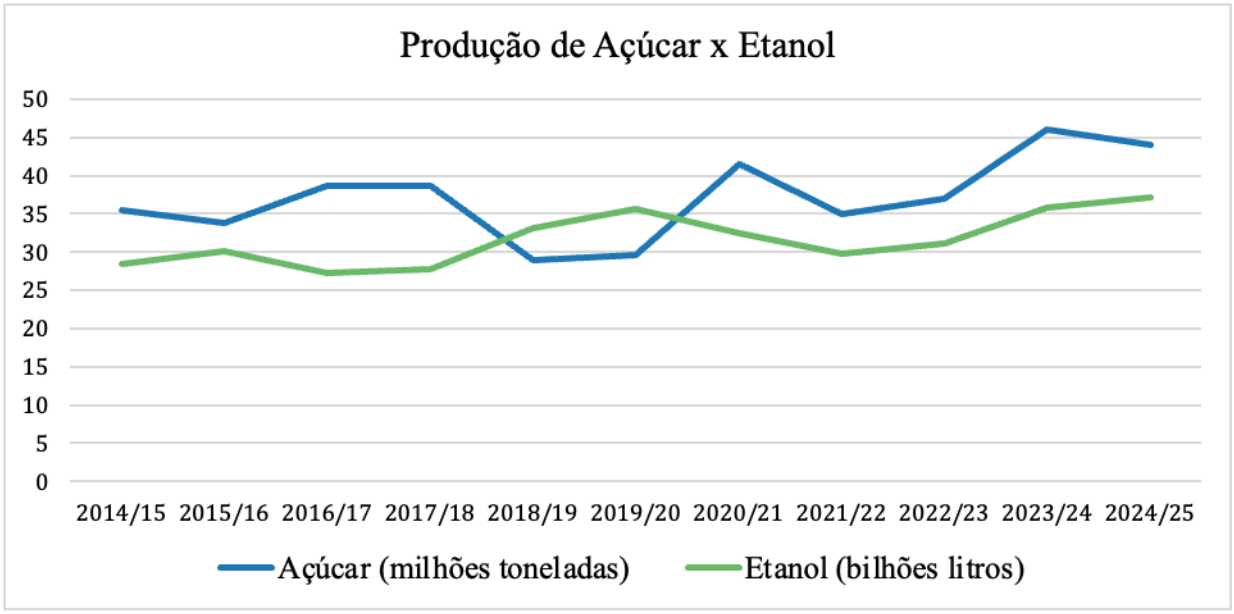
Along the same lines, Vidal (2024) projects that, in the short term, there is a trend toward more sugar-oriented harvests (such as 2024/25), with mills directing more feedstock toward sugar production rather than hydrous ethanol, due to high international commodity prices.

These projections carry uncertainties related to the exchange rate of the real against the dollar, which directly affects the sector's competitiveness in international and domestic markets. In addition, RenovaBio may influence the balance between sugar and ethanol, since the sugarenergy sector has high industrial flexibility to direct sugarcane toward sugar or ethanol

production, depending on the relative profitability of each product (Brasil, 2026; OECD-FAO, 2020).

The production flexibility of Brazilian mills, which allows switching between a focus on sugar or ethanol according to market profitability, is shown in Figure 7. It is observed that, in harvests such as 2020/21 and 2023/24, there was a clear prioritization of sugar (blue line), reflecting the sector's response to favorable international commodity prices. This dynamic shows that ethanol supply (green line) does not depend solely on installed capacity but also on strategic production-mix decisions that ensure the economic sustainability of industrial units in the face of exchange-rate and market volatility.

Figure 7 – Comparison of Brazilian sugar and ethanol production (2014/15 to 2024/25 harvests)



Source: Prepared by the authors based on data from UNICA (2025).

This scenario of productive duality reinforces the resilience of the national sugarenergy model, since the ability to rapidly adjust the production mix protects the sector against sudden fluctuations in isolated markets. Figure 7 illustrates that hydrous ethanol maintains its strategic relevance even in clearly "sugar-oriented" cycles, which ensures the supply of the flex-fuel fleet and the continuity of decarbonization targets. The integration between industrial efficiency and current regulatory frameworks ensures Brazil's competitiveness and prepares the agroindustry for the challenges of an evolving energy matrix.

5 Concluding remarks

This article sought to analyze the evolution of the Brazilian sugarenergy sector in the post flex-fuel period (2003-2025) and the factors that conditioned this trajectory. As a corollary, the consolidation of flex-fuel technology throughout the period analyzed became the main

structuring axis of the recent dynamics of the Brazilian sugarenergy sector. An environment of greater predictability was established, which sustains the expansion of ethanol production and reinforces its role as a buffer against fluctuations in international oil prices. In this context, the high share of the *flex* fleet in the country not only consolidated the domestic market but also enabled a growth trajectory based on a more resilient and adaptable energy matrix.

At the same time, the geographic reconfiguration of production, with emphasis on the expansion toward the Center-West and the incorporation of corn as a complementary feedstock, represented one of the most significant transformations of the sector in the 21st century. The introduction of corn ethanol, initially associated with the use of production surpluses, rapidly evolved into an integrated industrial model, capable of operating year-round and reducing plant idle time. This movement not only expanded the national biofuel supply but also strengthened the links between different production chains, especially by generating co-products relevant to livestock farming, contributing to production intensification and more efficient use of agricultural resources. This combination allowed the country to overcome limitations, such as sugarcane seasonality, while also enhancing energy security and the sector's international competitiveness.

Added to this productive integration, the evolution of the institutional and regulatory apparatus, with emphasis on the implementation of RenovaBio, consolidated ethanol as a strategic environmental asset on the global climate agenda. The transition from a model of direct subsidies to a CBIO market rewarded energy efficiency and encouraged a reduction in the carbon footprint throughout the chain. This advance, combined with the guidelines of the 2024-2035 Plano Clima, positions Brazil on a distinctive decarbonization path, in which hybridization and the use of biofuels offer an economically viable and technologically accessible alternative to the pure electrification trend observed in the Northern Hemisphere.

At the center of the international debate, the empirical evidence from this study refutes the alleged dichotomy between energy production and food security in Latin America. Bioenergy expansion occurs synergistically with food production, especially through sequential cropping and the generation of nutritionally valuable co-products. Food insecurity is attributed to macroeconomic crises and inflation, not to territorial occupation by energy crops, which occupy a small share of the territory.

The biofuel agroindustry, when supported by robust institutional structures, acts as an engine of socioeconomic development and regional technological sovereignty. Overcoming the traditional model of raw material exportation, replaced by the generation of bioproducts in integrated biorefineries, catalyzes the restructuring of the productive matrix. This paradigm reconciles climate resilience with sustainable economic growth, reducing the vulnerability of the

region's countries to the volatility of international oil prices, which strengthens GDP stability.

However, to achieve a full bioeconomy in the future, it is essential to integrate innovations with the complex geopolitical dynamics of Latin America. Future research should prioritize comparative analyses of the strategies implemented by Mercosur countries, with an emphasis on adding value to primary products and integrating production chains. Building a development model grounded in technological innovation becomes necessary for the region to transcend its role as a commodity exporter.

As a suggestion for future studies, it is worth investigating why the sugarenergy sector, prominent in some regions, does not achieve the same performance in the Northeast region, whose potential could, *mutatis mutandis*, drive its regional development. Methodologies for this could include econometric analyses and/or the application of questionnaires to key industry players and public-policy makers.

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