Impactos Energéticos, Ambientais e Socioeconômicos das Usinas Flex de Etanol

Energy, Environmental, and Socioeconomic Impacts of Flex Ethanol Mills

Laís de Sousa Abreu Soares
Doutoranda na Universidade Federal de Viçosa. Viçosa, Estado MG, Brasil
Leonardo Chaves Borges Cardoso
Professor Associado do Departamento de Economia Rural na Universidade Federal de Viçosa. Viçosa, MG, Brasil
Graziella Magalhães Candido de Castro
Professora Adjunta do Departamento de Economia da Universidade Federal de Juiz de Fora. Juiz de Fora, MG, Brasil

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Resumo: O estudo analisa os impactos energéticos, ambientais e socioeconômicos da adoção do modelo flex de produção de etanol no Brasil, que integra o uso de cana-de-açúcar e milho. Utilizando dados em painel para municípios brasileiros entre 2010 e 2023, aplica-se a metodologia de Diferenças-em-Diferenças duplamente robusta para estimar efeitos causais. Os resultados indicam que a adoção do modelo flex está associada a um aumento modesto no consumo relativo de etanol, refletindo maior competitividade frente aos combustíveis fósseis ao longo do ano. Observa-se também redução nas emissões per capita de gases de efeito estufa, sugerindo ganhos ambientais decorrentes da substituição de combustíveis fósseis. No âmbito socioeconômico, verifica-se crescimento do emprego total, com destaque para o setor agropecuário. Os achados indicam que a diversificação de matérias-primas contribui para reduzir a sazonalidade produtiva, ampliar a eficiência operacional e promover benefícios simultâneos nas dimensões energética, ambiental e econômica.
Palavras-chave: Milho; Cana-de-açúcar. Produção de etanol. Impactos ambientais. Impactos socioeconômicos.

Abstract: This study analyzes the energy, environmental, and socioeconomic impacts of adopting the flex model of ethanol production in Brazil, which integrates sugarcane and corn as feedstocks. Using panel data for Brazilian municipalities from 2010 to 2023, a doubly robust Difference-in-Differences approach is applied to estimate causal effects. The results indicate that the adoption of the flex model is associated with a modest increase in relative ethanol consumption, reflecting improved competitiveness compared to fossil fuels throughout the year. A reduction in per capita greenhouse gas emissions is also observed, suggesting environmental gains from the substitution of fossil fuels. From a socioeconomic perspective, there is an increase in total employment, particularly in the agricultural sector. The findings suggest that feedstock diversification helps reduce production seasonality, improve operational efficiency, and generate simultaneous benefits across energy, environmental, and economic dimensions.
Keywords: Corn. Sugarcane. Ethanol production. Environmental impacts. Socioeconomic impacts.

1. Introduction

The energy transition and the need to reduce greenhouse gas emissions have reinforced the role of biofuels in the energy matrix of several countries. In Brazil, ethanol has occupied a strategic position since the implementation of the National Alcohol Program (Proálcool), consolidating itself as one of the main instruments for replacing fossil fuels in the transportation sector (Wilkinson and Herrera, 2010). According to Karp et al. (2021), domestic production has historically been based on sugarcane, whose energy efficiency and favorable environmental performance have made the country an international benchmark in biofuel production.

The production of ethanol from sugarcane has a significant structural limitation: its seasonality. The existence of only one annual harvest and the impossibility of prolonged storage of the raw material imply a partial shutdown of industrial activities during the off-season (Milanez et al., 2014). As a result, a significant portion of productive assets remain idle for several months of the year, affecting the dilution of fixed costs and contributing to fluctuations in the supply and prices of ethanol (Neves et al., 2021; Silva and Castañeda-Ayarza, 2021).

In this context, the adoption of the so-called flex model for corn ethanol production emerges as a strategy for diversifying production capable of attenuating the effects of seasonality. Taking advantage of a scenario of considerable increase in corn production in the country, as noted by Milanez et al. (2014), flex plants began to process corn together with sugarcane, either exclusively during the off-season (non-integrated model) or throughout the year (integrated model). This configuration allows for more intensive use of existing structures, reducing asset idleness and extending the annual operating period of production units.

Despite the adoption of the flex model in Brazil over the last decade, the literature still lacks systematic empirical evidence on its energy, environmental, and socioeconomic impacts. The study conducted by Milanez et al. (2014) provides a descriptive assessment, based on interviews with firms operating at the time, of the environmental and economic performance of flex ethanol plants in Brazil. In contrast, my study aims to perform an econometric impact assessment of the energy, environmental and socioeconomic effects associated with the adoption of the flex model, within an ex-post framework in which the initial effects of its implementation are already evident.

From an economic standpoint, greater production stability may mitigate seasonal pressures on ethanol prices and enhance its competitiveness relative to fossil fuels. Moreover, as noted by Neves et al. (2021), the adoption of the flex model enables production expansion with comparatively lower investment requirements, as portions of the production, administrative, and commercial infrastructure of sugarcane-based ethanol can be shared with corn ethanol operations. Accordingly, this study seeks to examine whether these factors effectively strengthen ethanol competitiveness in the affected localities.

From an environmental perspective, Milanez et al. (2014) argue that the integration of sugarcane and corn in the Brazilian production context does not compromise the performance of the biofuel, either in terms of energy balance or reduction of greenhouse gas emissions. This outcome is largely attributable to the specific features of the Brazilian flex model, including the sharing of sugarcane bagasse-powered cogeneration infrastructure, which improves overall

process efficiency. Accordingly, this study also seeks to assess whether the adoption of the flex model contributes to reductions in greenhouse gas emissions in the affected localities.

From a socioeconomic perspective, the increase in demand for corn, industrial inputs, and logistics services can have effects on employment and income in producing regions. In addition, the generation of co-products, such as Distillers Dried Grains with Solubles (DDGS), expand the potential for upstream and downstream production chains related to the main activity Silva and Castañeda-Ayarza (2021). Accordingly, this study also seeks to examine whether the adoption of the flex model contributes to improvements in local socioeconomic conditions, particularly in terms of employment generation.

Besides the research conducted by Milanez et al. (2014), the existing literature has predominantly concentrated on the environmental assessment of sugarcane ethanol (De Oliveira and Coelho, 2017), or on the analysis of corn ethanol in international contexts, particularly in the United States (Wang et al., 2012). The limited number of studies addressing Brazilian corn ethanol (Silva and Castañeda-Ayarza, 2021; Gurgel et al., 2024; Eckert et al., 2018), typically examine production in a broader context, encompassing both flex plants and facilities that operate exclusively with corn feedstock, commonly referred to as full plants. However, the Brazilian institutional and productive arrangement marked by the integration of raw materials suggests that the effects of adopting the flex model may differ substantially from those observed in other countries and from the full model.

This article seeks to fill this gap by investigating the impacts of adopting the flex model of corn ethanol production on three key dimensions: (i) relative ethanol consumption, as a measure of bioenergy competitiveness; (ii) per capita greenhouse gas emissions; and (iii) total and sectoral employment levels in Brazilian municipalities. To this end, annual panel data for the period from 2010 to 2023 are used, and a doubly robust Difference-in-Differences strategy is applied, suitable for contexts with multiple periods and staggered adoption of the treatment, according to the approach proposed by Callaway and Sant'Anna (2021).

The results indicate that the adoption of the flex model is associated with an increase, albeit modest, in relative ethanol consumption, a reduction in per capita greenhouse gas emissions, and job growth in the municipalities treated, particularly in the agricultural sector. The evidence suggests that raw material diversification helps stabilize biofuel supply throughout the year, reduce net environmental impacts, and stimulate regional production chains.

This study contributes to the bioenergy literature by providing unprecedented causal evidence on the effects of the flex model in the Brazilian context. In addition, it offers relevant

insights for the debate on public policies for energy transition, indicating that organizational and technological innovations in the sugar-energy sector can generate energy, environmental, and socioeconomic benefits simultaneously.

2. Literature Review

2.1 Theoretical and empirical aspects

In Brazil, there are two types of distilleries that produce ethanol from sugarcane and corn, in a process known as flex. The first type is known as non-integrated flex, and corn ethanol production occurs only during the sugarcane off-season. The second type, known as integrated flex, processes both corn and sugarcane throughout the year, not limited to the sugarcane off-season (Neves et al., 2021).

The decision to adopt the flex model in sugarcane mills is closely associated with the strategic incentives to diversify feedstocks and enhance operational flexibility. The specific characteristics of sugarcane limit the time horizon for ethanol production using the product as a raw material on an annual basis: according to Neves et al. (2021), most sugarcane mills do not operate for about one-third of the year. This is because sugarcane has only one annual harvest and, due to its perishability, cannot be stored, preventing production from continuing during the off-season.

As a result, the productive, administrative, and commercial resources of these companies remain idle during the off-season. Nogueira Junior (2022) points out that, in this scenario, there is an incentive for companies to undergo a process of diversification of productive activity, specifically in the use of a new raw material in ethanol production, enabling the sharing of part of the idle resources within the mills during the off-season.

In terms of production resources, ethanol derived from sucrose-based feed stocks such as sugarcane follows a relatively direct biochemical pathway. According to Banco Nacional de Desenvolvimento Econômico e Social (2008), the process begins with the extraction of fermentable sugars through milling or diffusion. The extracted juice is then treated and sent directly to fermentation. After fermentation, the resulting mash is distilled, producing ethanol, which is hydrated when it does not undergo dehydration and anhydrous when it does undergo dehydration. This process occurs during the sugarcane harvest, so that the structures used remain idle during the off-season.

The integration of corn into the sugarcane ethanol production process can contribute to reducing the underutilization of certain resources. In the corn ethanol production process, the grain is received, stored, and cleaned before being milled, gelatinized, and hydrated. As sugars are not readily available in starch form, the process requires liquefaction, enzymatic hydrolysis,

and saccharification, through which starch is converted into fermentable sugars. These sugars are subsequently fermented, and the resulting mash is distilled to produce ethanol, following a procedure analogous to that used in sugarcane-based ethanol production (Banco Nacional de Desenvolvimento Econômico e Social, 2008).

Therefore, by also using corn as a raw material in ethanol production, both during the off-season and throughout the year (integrated mills), sugarcane ethanol producers reduce the idleness of the fermentation, distillation, dehydration, evaporation, and storage structures for the ethanol produced; so that these structures can be shared between corn and sugarcane ethanol. Despite the need for specific investments in structures related to the initial stages of grain processing, the integration between corn and sugarcane increases production capacity and contributes to the dilution of the company's fixed costs by reducing asset downtime (Neves et al., 2021).

In addition to this integration, it is important to highlight the potential use of the energy cogeneration infrastructure already established in sugarcane ethanol production units within the corn ethanol production process (Nogueira Junior, 2022). During the sugar extraction stage from sugarcane, whether by milling or diffusion, the sucrose rich juice is separated from the fibrous fraction (bagasse), which is subsequently directed to the cogeneration plant responsible for producing steam and electricity for the industrial process. According to Banco Nacional de Desenvolvimento Econômico e Social (2008), in the Brazilian context, bagasse-based cogeneration is typically self-sufficient and may generate energy surpluses that, under the flex production model, can be allocated to support corn ethanol production.

Finally, administrative resources, and particularly those related to ethanol commercialization, tend to be utilized more efficiently when production occurs continuously throughout the year. In the case of anhydrous or hydrated ethanol produced from corn, commercialization is carried out through the same logistical and distribution structures already established for this biofuel in sugarcane mills, since, upon leaving the plant, the product exhibits characteristics and specifications equivalent to those of ethanol derived from sugarcane (Neves et al., 2021).

Nogueira Junior (2022) points out that the adoption of corn as a feedstock for ethanol production represents a process of horizontal production diversification, consisting of the addition of a new product (corn ethanol) alongside the firm's traditional product (sugarcane ethanol), while exploiting operational, commercial, and administrative synergies. This approach allows the company to expand its product portfolio while maintaining a technological base relatively similar to that observed prior to diversification.

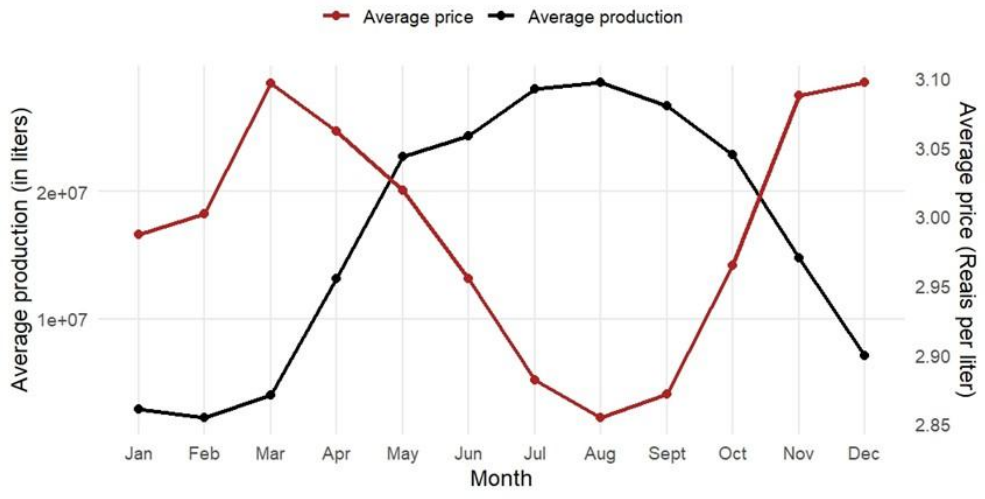
Despite this, there are specific factors that increase the likelihood of sugarcane mills adopting the flex production model. Diversifying the feedstock entails initial investments, an expansion of production scale, and the incorporation of an additional set of products and coproducts into the company's portfolio. In this context, both the investment capacity and the presence of prior knowledge and experience in complementary production stages contribute to reducing uncertainties, adaptation costs, and risks associated with the diversification process. Thus, as noted by Nogueira Junior (2022), the adoption of the flex production model is likely to be more feasible for mills that already possess these capabilities, making feedstock diversification not only a strategy for utilizing idle assets but also an economically viable option that aligns with previously developed organizational competencies.

2.1 Effects of Flex Distilleries

The adoption of the flex production model by sugarcane-based ethanol producers can generate significant effects on biofuel consumption, as well as environmental and socioeconomic impacts Milanez et al. (2014). Regarding hydrated ethanol relative to fossil fuel consumption, it should be noted that the flex model has largely been implemented in regions where sugarcane ethanol production is already established, which tends to support the maintenance of competitive prices compared to gasoline.

However, as noted by Neves et al. (2021), during the sugarcane off-season, domestic ethanol production declines, increasing the need for biofuel imports, primarily from the United States, which exerts upward pressure on domestic prices. As a result, between December and March, ethanol tends to lose competitiveness in these regions, becoming relatively less attractive compared to gasoline.

Figure 1: Evolution of average national ethanol production and average prices from 2013 to 2023.



Data from Unicadata. Notes: Ethanol production, measured in liters, represents the sum of anhydrous and hydrous ethanol produced annually in Brazil.

Figure 1 illustrates the evolution of average national ethanol production and average prices from 2013 to 2023. A marked decline in production is observed between November and March, corresponding to the sugarcane off-season, while average biofuel prices reach their highest levels during this period. This pattern highlights an inverse relationship between supply and price, indicating that the reduction in domestic production during the off-season contributes to upward pressure on prices, with potential negative effects on ethanol competitiveness relative to gasoline.

By adopting corn as a raw material to be processed alongside sugarcane in flex mills, distilleries can maintain operations throughout the year, rather than being restricted to the sugarcane harvest period. This flexibility is essential for optimizing the use of industrial facilities and ensuring continuous production throughout the year. As pointed out by Neves et al. (2021), flex mills typically operate between 330 and 350 days per year, which represents a significant advantage over traditional mills, which are limited to the duration of the sugarcane harvest.

In this context, the integration of corn ethanol technology, as highlighted by Silva and Castañeda-Ayarza (2021), constitutes an effective strategy to reduce periods of operational idleness. Moreover, it contributes to the dilution of operational costs and to an increase in production. These advantages ultimately result in more competitive biofuel prices throughout the year, particularly in regions where competitiveness was previously limited to a specific period.

In environmental and socioeconomic terms, Gurgel et al. (2024) point out that various approaches and modeling methods have been employed to assess bioenergy trajectories and their impacts, including bottom-up models, life cycle assessment and social life cycle assessment of fuels, system dynamics models, computable general equilibrium models, integrated assessment models, and hybrid models that combine some of these strategies.

Environmentally, the use of sugarcane ethanol as a substitute for gasoline has been evaluated positively regarding its greenhouse gas (GHG) emissions, as indicated in related studies (De Oliveira and Coelho, 2017; Goldemberg et al., 2008). Regarding corn ethanol, literature is still at an early stage. The analysis by Wang et al. (2012) presents results from simulations of greenhouse gas (GHG) emissions over the life cycle associated with the use of bioethanol produced from various feedstocks, including corn (with data from U.S. production) and sugarcane (with data from Brazilian production). The results indicated that, relative to

gasoline, corn ethanol produced in the United States can reduce life cycle GHG emissions by 19–48%, whereas sugarcane ethanol produced in Brazil can reduce life cycle GHG emissions by 40–62%.

However, corn ethanol production processes in the United States and Brazil have significant structural differences. In Brazil, corn ethanol production occurs under different industrial configurations, including flex and full models. Specifically in the flex model, which is the focus of this article, it should be noted that most of the energy used in the production process comes from sugarcane biomass (bagasse), through cogeneration structures already existing in sugar and ethanol mills Milanez et al. (2014). In contrast, in US corn ethanol production, energy cogeneration from fossil fuels is one of the main contributors to GHG emissions throughout the biofuel life cycle (Neves et al., 2021).

In addition, the configuration of flex mills, characterized by the sharing of production resources between the sugarcane ethanol and corn ethanol chains, imposes limits on the growth of grain-based production and, consequently, on the expansion of demand for corn (Nogueira Junior, 2022). This arrangement contributes to mitigating the environmental impacts associated with the intensification of agricultural production by reducing emissions linked to corn cultivation and the need to expand the areas devoted to its planting.

In socioeconomic terms, as noted by Silva and Castañeda-Ayarza (2021), corn ethanol production has the potential to generate positive impacts on employment and income in producing regions. In the context of flex plants, the possibility of year-round operation reduces the idleness of productive factors, including industrial labor. By enabling a more continuous production regime, these units mitigate the effects of the seasonality characteristic of the sugar energy sector, contributing to the maintenance of jobs during the sugarcane off-season. This operational pattern tends to enhance the stability of industrial employment, with positive effects on income predictability and the retention of skilled labor.

Additionally, the adoption of the flex production model may have significant impacts on the agricultural sector, particularly in the corn production chain, which serves as the main feedstock for corn ethanol, as well as on livestock activities due to the avail ability of Dried Distillers Grains with Solubles (DDGs), a co-product of the production process widely used in animal feed (Silva and Castañeda-Ayarza, 2021).

At the industrial level, corn ethanol production in flex plants also increases the demand for process-specific inputs, particularly the chemical and biotechnological products used in the enzymatic hydrolysis stage, which is responsible for converting starch into fermentable sugars (Neves et al., 2021). Furthermore, the operation of these units increases the demand for

transportation and logistics services, both for the supply of raw materials and industrial inputs and for the distribution of biofuel and its co-products (Silva and Castañeda-Ayarza, 2021).

In summary, the adoption of the flex production model has the potential to induce chain socioeconomic effects by fostering greater integration among the industrial, agricultural and logistics sectors. The reduction of production seasonality contributes to the stabilization of industrial employment, while the strengthening of input supply chains and upstream and downstream sectors enhances income generation and the diversification of regional economic activities. These productive linkages reinforce the local economic dynamism of producing regions.

3. Methodology

3.1 Empirical Strategy

This article aims to investigate the energy, environmental, and socioeconomic impacts of adopting corn ethanol technology based on the flex model in Brazil. To this end, panel data is used and a doubly robust Difference-in-Differences approach is employed, as proposed by Sant'Anna and Zhao (2020) and Callaway and Sant'Anna (2021).

The canonical Differences-in-Differences (DiD) model is widely used for estimating causal effects in non-experimental settings. Its framework involves two periods and two groups: a treatment group that receives the intervention in the second period, and a control group that does not receive the treatment in either period. The main parameter of interest in the conventional DiD model is the Average Treatment Effect on the Treated (ATT), which measures that average causal effect on treated units in the period they were treated (Roth et al., 2023).

However, in practice, not all applications meet the requirements of the canonical Differences-in-Differences framework. In the context of this study, the adoption of the flex model of ethanol production involves multiple periods and units (municipalities) that are treated at different points in time. The treatment occurs when a municipality *i*, in which ethanol is produced from sugarcane, adopts the flex model (producing biofuel from sugarcane and corn) in period *t*. Thus, the treatment group consists of municipalities that produce ethanol from sugarcane and have adopted the flex production model, while the control group consists of municipalities that produce ethanol exclusively from sugarcane.

Thus, I adopt the identification strategy proposed by Callaway and Sant'Anna (2021), which generalizes the conventional Difference-in-Differences method, providing a framework for estimating causal effects that allows for: (a) multiple periods; (b) staggered treatment adoption and (c) treatment heterogeneity, either over time or between groups.

Unlike the conventional DiD approach, the doubly robust Differences-in-Differences method does not focus on a single parameter, such as the ATT. Instead, it estimates several group-time average treatment effect parameters. These groups are defined by the time at which a unit is first treated, and each specific group-time average treatment effect parameter, denoted as ATT (g, t), represents the causal effect of the treatment at time *t* for the group of units first treated at time *g*. The ATT (g, t) is identified by comparing the expected change in outcome for treatment cohort *g* between $g-1$ and *t* to that for a control group of never treated units:

$$ATT\ (g,t) = E[Y_{i,t} - Y_{i,g-1}|G_i = g] - E[Y_{i,t} - Y_{i,g-1}|G_i = \infty] \quad (1)$$

Where *i* indexes city and *t* denotes year. Y is the outcome variable and G_i is the earliest period at each unit has received treatment. In this case, the treatment group is defined by conditioning the value of the adoption date, and the control group is defined as all groups that never adopted treatment, known as the never-treated group.

The estimation of ATT (g, t) is based on the same two central assumptions as the canonical model, but in a more flexible formulation. The no anticipation assumption in the reformulation proposed by Callaway and Sant'Anna (2021) is replaced by the limited anticipation assumption, which allows treated units to anticipate the treatment as long as the anticipation horizon is well-defined. Meanwhile, the parallel trends assumption in the Callaway and Sant'Anna (2021) model constitutes a generalization in which this assumption is considered valid conditionally on a set of covariates that affect both the probability of treatment and the temporal trend of the outcome variable.

However, in the present study, these assumptions are considered valid in a more restricted manner, similarly to the canonical model. The adoption of the flex model constitutes a competitive strategy for sugarcane ethanol producers and is strongly associated with firm-specific characteristics, such as technical capacity, availability of capital, and financial conditions. It is reasonable to assume that these factors influence the likelihood of adopting the model but do not directly affect the temporal trajectory of the outcome variables, such as relative ethanol consumption, greenhouse gas emissions, and employment levels in the municipalities where the plants are located.

Additionally, the adoption of the flex model is a strategic decision made within firms and involves investments that are both limited in magnitude and concentrated in specific periods. In this context, it is plausible to assume the absence of anticipatory effects, since the impacts of the treatment are likely to occur only after the model is effectively implemented.

Finally, the definition of treatment and control groups does not explicitly incorporate a spatial dimension. The treated group consists of municipalities that adopted the flex model,

while the control group includes municipalities that produce ethanol exclusively from sugarcane. It is noteworthy that there is not necessarily geographic proximity between treated and control municipalities, which reduces the plausibility of direct spatial interactions. Therefore, the occurrence of spatial spillovers is considered unlikely Thus, it is plausible to assume the absence of spillovers, as proposed in the Callaway and Sant'Anna (2021) framework.

Finally, the method proposed by Callaway and Sant'Anna (2021) provides a flexible framework for summarizing the group-time average treatment effects (ATTs) estimated in the first stage. The aggregation can be done in different ways, depending on the research question: by exposure time, by groups and by calendar-time.

3.2 Data

The data used in this study include information on all Brazilian municipalities on an annual basis for the period 2010–2023. To construct the treated and control groups, data from the National Agency of Petroleum, Natural Gas, and Biofuels (ANP) were used. The ANP is a government agency responsible for regulating activities in the petroleum, natural gas, and biofuels sectors. It also serves as a central repository of data related to production, consumption, prices, market regulation, quality standards, as well as research and innovation in the fuel sector.

The treated group consists of municipalities in which at least one sugarcane ethanol plant adopted the flex production model, that is, began processing sugarcane and corn simultaneously. The control group, in turn, is composed of municipalities that host only plants producing ethanol exclusively from sugarcane.

The information used was extracted from the ANP's Dynamic Panel of Ethanol Producers, which provides tabulated data on ethanol plants authorized to operate in the country, including their location and the feedstocks used in the production process. From this database, twelve ethanol plants that utilize both sugarcane and corn as inputs were identified.

Subsequently, a documentary analysis was conducted to identify the year in which each of these plants adopted the flex model, using data from ANP and information reported in studies such as Nogueira Junior (2022) and Neves et al. (2021). It was found that, of the twelve identified plants, ten began processing corn together with sugarcane by 2023, while the remaining two adopted corn processing after the temporal window considered in this study. Of the ten plants that adopted the flex model between 2010 and 2023, two are located within the same municipality. Thus, the treated group comprises nine municipalities. These data are presented in Table I.

Table I: Plants that adopted the flex model between 2010 and 2023

Municipality	State	Firm	Year of adoption of the flex model (G)
Campos de Júlio	MT	Usimat Destilaria de Álcool LTDA.	2012
São José do Rio Claro	MT	Destilaria de Álcool Libra LTDA.	2012
Jaciara	MT	Porto Seguro Negócios, Empreendimentos & Participações S.A.	2014
Rio Verde	MT	Usina Rio Verde LTDA.	2015
Quirinópolis	GO	Cargill Bioenergia LTDA.	2015
Vicentinópolis	GO	Caçu Comércio e Indústria de Açúcar e Álcool LTDA	2018
Jandaia do Sul	PR	Cooperval Cooperativa Agroindustrial Vale de Ivaí LTDA.	2019
Santa Helena de Goiás	GO	Usina Santa Helena de Açúcar e Álcool S/A	2019
Campo Novo do Parecis	MT	Cooperativa Agr. Prod. Cana de Campo Novo do Parecis LTDA.	2020
Quirinópolis	GO	São Martinho S/A	2023

Elaborated by the author.

The study by Neves et al. (2021) adds to the plants presented in Table I the plant Cereale Brasil Agroindustrial LTDA., located in Dois Córregos, in the state of São Paulo. However, this plant is indicated in the ANP authorizations as an exclusive corn processor. Thus, it was disregarded in this study.

Figure 2: Spatial distribution of flex ethanol plants and sugarcane-exclusive ethanol plants in Brazil

Elaborated by the author. Note: The left panel displays the location of flex ethanol plants (orange), and the right panel presents the location of sugarcane-only ethanol plants (green).

Regarding the control group, as of 2025, 320 plants process sugarcane exclusively, distributed across 273 municipalities. As shown on the right-hand side of Figure 2, most of these plants are in the Center-South region of the country, with a strong concentration in the state of São Paulo, the leading sugarcane-producing federative unit in Brazil. Figure 2 also displays the location of the flex plants on the left-hand side, which are predominantly concentrated in the Center-West region.

With the primary objective of this paper in mind, which is to assess the energy, environmental, and socioeconomic impacts of adopting the flex model, six outcome variables are analyzed: relative ethanol consumption, GHG emissions, total employment, and

employment by sector (rural, industrial, and services). The first variable pertains to the relative ethanol consumption in municipality *i* in year *t*, constructed to capture the share of hydrated ethanol in total fuel consumption while accounting for the differences in energy efficiency between ethanol and gasoline:

$$Relative\ Ethanol\ Consumption_{it} = \frac{0{,}7\ x\ Hydrous\ Ethanol\ Consumption_{it}}{Gasoline\ Consumption_{it} + 0{,}7\ x\ \ Hydrous\ Ethanol\ Consumption_{it}} \quad (2)$$

Where subscript *i* denotes the municipality and subscript *t* denotes the reference year. Data on hydrous ethanol and gasoline consumption are obtained from the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP). The incorporation of the factor 0.7 in the construction of the variable stems from the lower energy efficiency of hydrated ethanol compared to gasoline. Empirical literature, including studies by Pacini and Silveira (2011) and Orellano et al. (2013), as well as a rule of thumb widely accepted among the population, indicate that ethanol becomes economically more attractive when its price corresponds to approximately 70% of the price of gasoline.

The second outcome variable is greenhouse gas (GHG) emissions. Emissions data are drawn from the Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa (SEEG), an initiative of the Observatório do Clima. The variable related to emissions that will be used for analysis in this study corresponds to:

$$Per\ Capita\ Emissions_{it} = \log\left(\frac{CO_2e\ emissions_{it}}{Population_{it}}\right) \quad (3)$$

Where CO_2e emissions denote gross GHG emissions, measured in carbon dioxide equivalent, in municipality *i* at time *t*, and Population denotes the corresponding municipal population.

The third variable of interest, which measures the socioeconomic impacts of adopting the flex model, is employment. Information related to employment is sourced from the Annual Social Information Report (RAIS). Employment is measured by:

$$Employment_{it} = \log\left(Formal\ Employment\ Ties_{it}\right) \quad (4)$$

Where Formal employment ties correspond to the number of formal employment contracts registered in municipality *i* in year *t*. In addition to total employment, the analysis also considers disaggregated measures by major economic sectors, as defined by the Brazilian Institute of Geography and Statistics (IBGE): rural (agriculture and livestock), industry, and services. In these cases, the variable assumes the same functional form, differing only in the sectoral scope of formal employment ties, namely: rural employment, industrial employment, and services employment.

4. Results

The analysis of empirical results begins with assessing the impact of the shock associated with the adoption of the flex model in municipalities that have sugarcane ethanol plants. The estimates presented were obtained using a doubly robust differences in-differences estimator, considering as a control group those municipalities that were never treated, namely those with plants producing ethanol exclusively from sugarcane. The first step in assessing the impact of adopting the flex model was to estimate specific models for each combination of groups of municipalities belonging to the same cohort *g* (defined by the initial year of treatment) in each period *t*.

Given the high number of estimates generated, this section presents the results with a focus on two types of aggregation of the estimated parameters. First, the parameters are aggregated by treatment group to obtain group-level average treatment effects. Finally, an overall average effect is computed across groups, summarizing the mean impact of the treatment on each outcome variable of interest. Next, the estimates of the dynamic effects of the treatment on these variables over time are presented. Specifically, we assess how the impact of adopting the flex model evolves each year relative to the start of the treatment, allowing us to observe both the immediate effects and the medium and long-term effects. These results are presented using event study graphs, which illustrate the temporal trajectory of the estimated effects before and after the adoption of the treatment.

Table II: Overall Treatment Effect Estimates - Flex

Treatment: Adoption of the flex model of corn ethanol production	Overall Treatment Effect (ATT)	Std. Error
Relative Ethanol Consumption	0.013***	0.004
Emissions Per Capita	-0.063***	0.019
Overall Employment	0.086***	0.033
Rural Employment	0.204***	0.026
Industrial Employment	0.078**	0.015
Services Employment	0.043***	0.014

Source: Authors. ***: Statistically significant at the 1% level; **: Statistically significant at the 5% level; *: Statistically significant at the 10% level.

Table II presents the Overall Treatment Effect for each variable of interest. According to Table II, the estimated average total effect of the adoption of the flex model on relative ethanol consumption is 0.013, statistically significant at the 1% level. This indicates that, on average, the adoption of corn processing in sugarcane mills led to an increase, albeit small, in relative ethanol consumption in the treated municipalities compared to what would have occurred in the absence of the treatment.

This finding reinforces the potential of flex technology to enhance ethanol competitiveness relative to gasoline in a more stable manner throughout the year, particularly in locations where ethanol is already competitive during the sugarcane harvest season. The increase in production, combined with the use of existing operational, commercial and distribution structures in these municipalities, likely reduces the need for ethanol imports during the sugarcane off-season and, consequently, affects prices. As a result, ethanol may be sold at more competitive price levels even during months when, prior to the adoption of the flex model, plants were not operating.

The estimated average treatment effect on emissions is -0.063 and statistically significant at the 1% level. This suggests that the adoption of flex corn ethanol plants led, on average, to a 6.3% reduction in CO_2 equivalent emissions in treated municipalities. This result indicates that the emission reductions associated with the substitution of fossil fuels by ethanol, driven by increased production, are sufficient to offset potential increases in emissions arising from the corn ethanol production process. The finding is consistent with the fact that flex processing largely relies on existing infrastructure and energy sources already used in sugarcane ethanol production, thereby reducing the need for additional facilities or energy inputs.

The estimated average treatment effect on total employment is 0.086 and statistically significant at the 1% level, indicating an average increase of 8.6% in employment in treated municipalities. When disaggregated by sector, the estimated effects are 0.204 for agricultural employment, 0.078 for industrial employment, and 0.043 for services employment, with all coefficients significant at the 1% level.

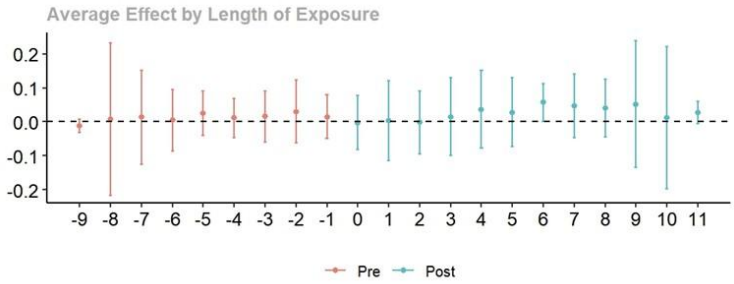
These results suggest that the expansion of flex ethanol plants promotes job creation, particularly in the agricultural sector, through a series of upstream and downstream linkages. The increased demand for corn to supply these mills encourages the expansion of local cultivation. Unlike plants exclusively dedicated to corn, which tend to be located in regions where production is already consolidated (Silva and Castañeda Ayarza, 2021) due to the need for large volumes of the input (Neves et al., 2021), flex plants operate with limitations on the use of corn, which favors the stimulation of local production development, rather than dependence on large production centers.

Moreover, corn ethanol production generates co-products such as Distillers Dried Grains with Solubles (DDGS), which are widely used in animal feed. Greater availability of these inputs reduces costs for livestock producers, encourages intensification and expansion of agricultural activities, and strengthens local production chains, contributing to increased rural employment.

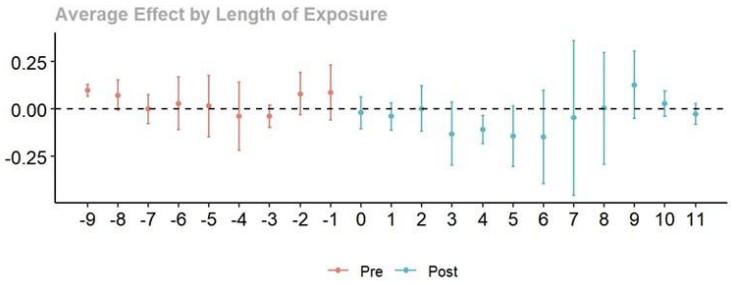
The positive effect on industrial employment is consistent with the fact that the adoption of the flex model allows production to continue beyond the period restricted to the sugarcane harvest season (Milanez et al., 2014). This contributes to greater employment stability in ethanol plants and in industries supplying inputs to the production process. Furthermore, the incorporation of this technology stimulates the development of sectors directly associated with corn processing, such as chemicals, biotechnology, machinery and equipment, transportation, storage, and commercialization, thereby amplifying positive effects on both industrial and services employment.

Figure 3 presents the dynamic treatment effects on relative ethanol consumption (a), emissions per capita (b), and total employment (c). The red lines represent differences between treatment and control groups in the pre-intervention periods, while the blue lines illustrate the aggregated treatment effects across groups in the post intervention periods.

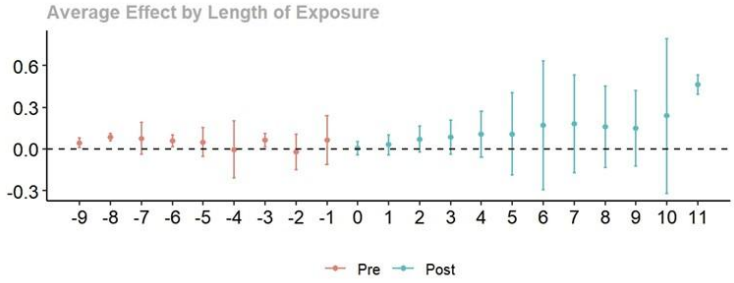
Figure 3: Event Study – Treatment: Adoption of the flex model



(a) Relative Ethanol Consumption



(b) Emissions



(c) Overall Employment

In all three cases, the pre-treatment estimates are close to zero and show no systematic trend prior to the adoption of the flex model, lending support to the parallel trends assumption, consistent with Callaway and Sant'Anna (2021). The relatively wide confidence intervals, both before and after treatment, may reflect the limited number of treated units, given that the adoption of this technology remains a relatively recent phenomenon in Brazil.

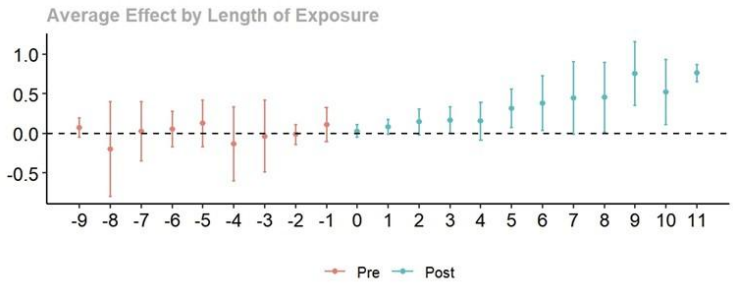
For relative ethanol consumption (a), in the immediate post-treatment years, the coefficients remain close to zero and are not statistically distinguishable from zero, indicating

no immediate impact of the adoption of the flex model on relative ethanol consumption. A small positive effect begins to emerge approximately three years after the intervention, with point estimates turning positive and modestly increasing. However, the magnitude of this effect remains limited, and the confidence intervals suggest that it is not consistently statistically significant across subsequent periods.

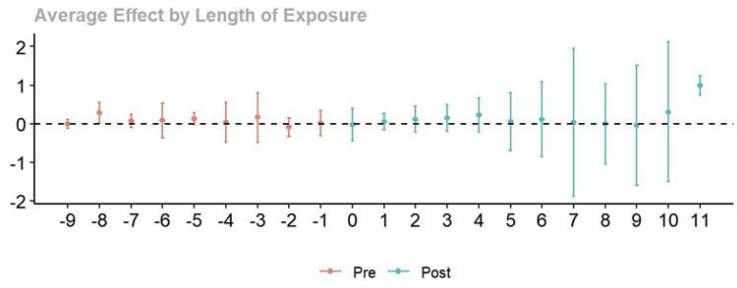
For emissions (b), approximately three years after the intervention, the point estimates become predominantly negative, with several post-treatment coefficients lying below zero. This shift coincides with the period in which relative ethanol consumption exhibits a modest positive effect, suggesting a potential substitution mechanism whereby increased ethanol use is associated with lower per capita emissions. Although the magnitude of the estimated effects varies over time and confidence intervals widen in some later periods, the overall post-treatment pattern is consistent with a reduction in emissions following the adoption of the flex model.

In the case of employment (c), following the intervention, the estimated effects turn positive approximately two years after the adoption of the flex model and remain positive throughout subsequent periods. Moreover, the magnitude of the coefficients exhibits a gradual upward trajectory over time, suggesting that the employment effects intensify with longer exposure to treatment.

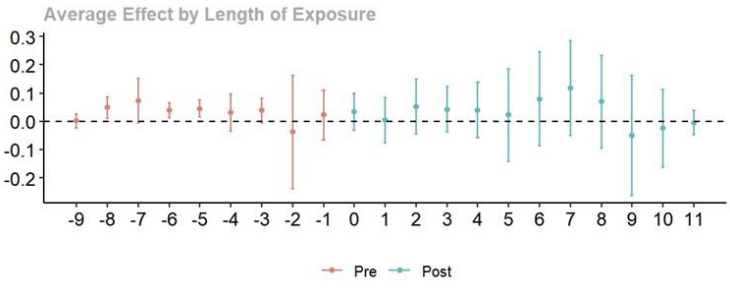
Figure 4: Event Study– Treatment: Adoption of the flex model (Employment by sector)



(a) Rural Employment



(b) Industrial Employment



(c) Services Employment

Figure 4 presents the dynamic treatment effects on agricultural employment (a), industrial employment (b), and services employment (c). As in Figure 4, Figure 5 presents that

the pre-treatment estimates in all three cases are close to zero and do not exhibit any systematic trend prior to the adoption of the flex model, lending further support to the parallel trends assumption (Callaway and Sant'Anna, 2021).

For rural employment (a), in the post-treatment period, the estimated effects become positive shortly after the intervention and increase steadily with longer exposure. The magnitude of the coefficients grows over time, and several later estimates are economically large, suggesting that the impact of the flex model on rural employment strengthens as plants consolidate corn-based operations. This pattern may be explained by the rising demand for corn as well as by spillover effects on livestock activities resulting from the greater availability of Distillers Dried Grains with Solubles (DDGS).

In the services sector (c), the event-study coefficients indicate a modest positive effect in the first years following treatment, suggesting that the adoption of the flex model may initially stimulate service-related activities in treated municipalities. However, the magnitude of the estimates declines over time, and confidence intervals widen in later periods, reducing the precision of the long-run effects.

By contrast, for industrial employment (b), the dynamic coefficients remain close to zero in most post-treatment years, and several estimates are imprecisely estimated. Although the aggregated average treatment effect is positive and statistically significant, the event-study results do not reveal a clear or consistent upward trajectory over time. Therefore, it is not possible to rule out the hypothesis that the adoption of the flex model did not generate a substantial dynamic impact on industrial employment, despite the positive average effect identified in the pooled estimates.

The results provide consistent evidence that the adoption of the flex model contributes positively to energy, environmental, and socioeconomic outcomes in Brazilian municipalities. Although some estimates exhibit limited precision, likely due to the relatively small number of treated units and the recent diffusion of the technology, the overall patterns are robust and economically meaningful.

5. Final Considerations

This study investigated the energy, environmental, and socioeconomic impacts of adopting the flex model of ethanol production in Brazil. By integrating sugarcane and corn as feedstocks, the flex model emerges as an important technological and organizational innovation capable of addressing structural limitations associated with seasonality in the sugar-energy sector.

The empirical evidence indicates that the adoption of the flex model contributes to a modest increase in relative ethanol consumption, suggesting improved competitiveness of biofuels in relation to fossil fuels. In environmental terms, the results point to a reduction in per capita greenhouse gas emissions, reinforcing the potential of the Brazilian production model, characterized using biomass-based energy, to deliver sustainable outcomes. From a socioeconomic perspective, the findings reveal positive effects on employment, particularly in the agricultural sector, highlighting the role of production diversification in stimulating local economies and strengthening regional production chains.

Taken together, these results suggest that the flex model promotes a more stable, efficient, and sustainable bioenergy system. The reduction of production seasonality, combined with the better use of existing infrastructure, contributes to increased operational efficiency and economic resilience. Moreover, the integration of agricultural and industrial activities generates spillover effects that extend beyond the energy sector.

Despite these contributions, the study is subject to limitations, including the relatively recent adoption of the flex model and the limited number of treated units, which may affect the precision of some estimates. Future research could expand the analysis by incorporating plant-level data, exploring regional heterogeneities, and assessing long-term impacts as the technology becomes more widespread.

In terms of policy implications, the findings highlight the importance of supporting technological innovations that enhance resource efficiency and promote integration across production chains. Encouraging the adoption of the flex model may represent a relevant strategy for advancing the energy transition while simultaneously fostering environmental sustainability and regional development in Brazil.

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