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Socioeconomic Effects of Proalcool: Economic Growth and Development

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ABSTRACT

The establishment of Proalcool five decades ago not only substantially boosted the production of sugarcane, sugar, and ethanol in Brazil but also generated considerable effects on the labor market and contributed to the economic growth and development of various Brazilian regions. We reviewed the evolution of socioeconomic indicators and recent research on Brazil's sugarcane, sugar, and ethanol sectors, covering employment data, working conditions, impacts of mechanical harvesting, broader socio-economic effects, and foreign currency savings. In summary, alongside fostering economic growth and development within Brazilian municipalities, the expansion of these sectors significantly contributes to employment generation and enhancing the agricultural labor market.

1 | Introduction

Proalcool, launched in Brazil in November 1975 to promote ethanol as an alternative to gasoline in response to the petroleum crisis, significantly transformed the nation's sugarcane, sugar, and ethanol industries. Since its introduction, ethanol production expanded from approximately 555 million liters to 30 billion liters by 2024, driving a remarkable increase in national sugarcane output and fostering the development of new cultivation areas beyond traditional regions [1].

Sugarcane production rose from 68.3 million tons to 676 million tons—a growth of 889% while cultivated areas expanded from 1.9 million hectares to 8.8 million hectares, reflecting a 363% increase over the same period [1].

This expansion also had a significant impact on employment in the sector, which peaked at 1,283,258 formal jobs in 2008. By 2024, however, employment had declined to 749,930, primarily due to the mechanization of sugarcane harvesting, which accounts for 92.4% of national production nowadays [1, 2].

Moreover, the industry's transition to ethanol as a substitute for gasoline has led to significant foreign currency savings and reduced inflationary pressure by decreasing oil imports during a period of rising prices. Between 1975 and 2023, 3.6 billion barrels of gasoline were replaced with ethanol, resulting in reported savings exceeding 725 billion constant dollars as of December 2023 [3].

In an era of increasing production and utilization of sugarcane ethanol in Brazil and globally—primarily driven by its environmental advantages as a more sustainable alternative to gasoline—it is crucial to highlight the socioeconomic dimensions of its production.

Although extensive literature exists on the environmental impacts of sugarcane, sugar, and ethanol production, comparatively

little research has been dedicated to the social aspects. A deeper understanding of these dimensions can contribute to improving labor practices, assessing the impacts on local development and economic growth, and guiding policy decisions. Furthermore, such insights could be of relevance for countries considering the implementation of a biofuel program.

Section 2 provides a detailed analysis of statistics on sugarcane, sugar, and ethanol production, alongside consumption and employment data. Subsequent sections present a comprehensive literature review highlighting the socioeconomic dimensions of the industry, encompassing employment in agricultural and sugarcane sectors, the impact of mechanized harvesting on labor dynamics and worker migration, and the broader socioeconomic impacts of Brazil's sugarcane industry.

2 | Evolution of Production, Consumption and Number of Jobs

Following the 1973 oil crisis, Brazil, which had maintained a stable trade balance prior to this period, began to accumulate a significant deficit due to fuel imports. The Brazilian trade balance shifted from a slightly positive balance of 7 million dollars in 1973 to a negative balance of 4.6 billion dollars in 1974, primarily driven by a 388% increase in the value of oil and derivatives imports between 1973 and 1974 [4].

Following the implementation of Proalcool, the program's initial focus on alleviating the country's trade balance began to shift, driven more recently by increases in the production and consumption of biofuels, with the rise of the low-carbon economy and the growing global demand for alternative and renewable energy sources.

Figure 1 illustrates the process of production growth, highlighting the significant increase in fuel ethanol production up to 1985—driven by strong government action within the program—followed by a period of relative stagnation until the early 1990s, and a new growth phase from the 2000s onwards. This latter phase was shaped by the cessation of government intervention, the advent of flex-fuel vehicles, international investments, and the substantial growth in domestic and international demand for sugar and ethanol [5].

More recently, the production of corn ethanol in Brazil has also grown (Figure 1).

Proalcool was initiated as a strategy to balance the trade deficit, addressing the rising internal demand for fuels that surpassed domestic production and imports needs. As illustrated in Figure 2, Proalcool proved effective in stabilizing the country's trade balance concerning fuel, which was further catalyzed by the discovery of Brazilian oil reserves, particularly with the exploration of the pre-salt basin in 2007, when Brazil began exporting oil in greater volumes. Between 1975 and 2023, 3.6 billion barrels of gasoline were replaced by ethanol, and this substitution corresponds to savings exceeding 725 billion constant dollars as of December 2023 [3].

Since the late 2000s, ethanol production has faced a period of crisis driven by factors such as gasoline price control policies (tax reductions as an inflation control measure); low predictability in energy policies; preferential government incentives for other energy sources; rising labor costs; and restrictions on land acquisition by foreigners limiting investments; among other aspects [5, 8].

The decline in hydrous ethanol sales was reversed following the introduction of flex-fuel vehicles in March 2003. By allowing consumers to utilize gasoline, ethanol, or any combination thereof, flex-fuel technology provided a significant increase in user flexibility at the point of refueling rather than at the moment of vehicle purchase. This advantage contributed substantially to the success of flex-fuel vehicles. The adoption of flex-fuel engine technology, combined with positive developments in the international market, has revitalized Brazil's fuel sector. This changing technological and economic market has created promising opportunities for the ethanol industry, prompting substantial investments aimed at increasing ethanol production capacity [5].

FIGURE 1 | Brazilian production of sugarcane, sugar, and ethanol: Crop year 1975–76 to 2025–26. *Source:* Prepared by the authors based on data from Conab [1]. Data for the 2025–26 crop year refer to a forecast.

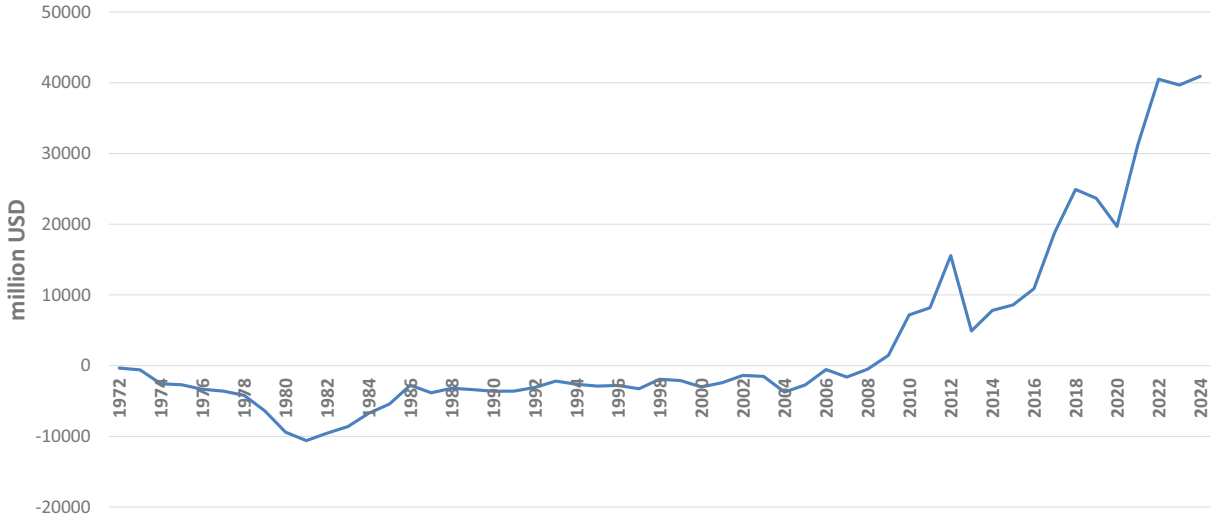

FIGURE 2 | Brazil's trade balance (exports and imports) of oil, gasoline, and ethanol (in aggregated values, in USD million current). *Source:* Prepared by the authors based on data from Oliveira [6]. Trade Data Monitor [7].

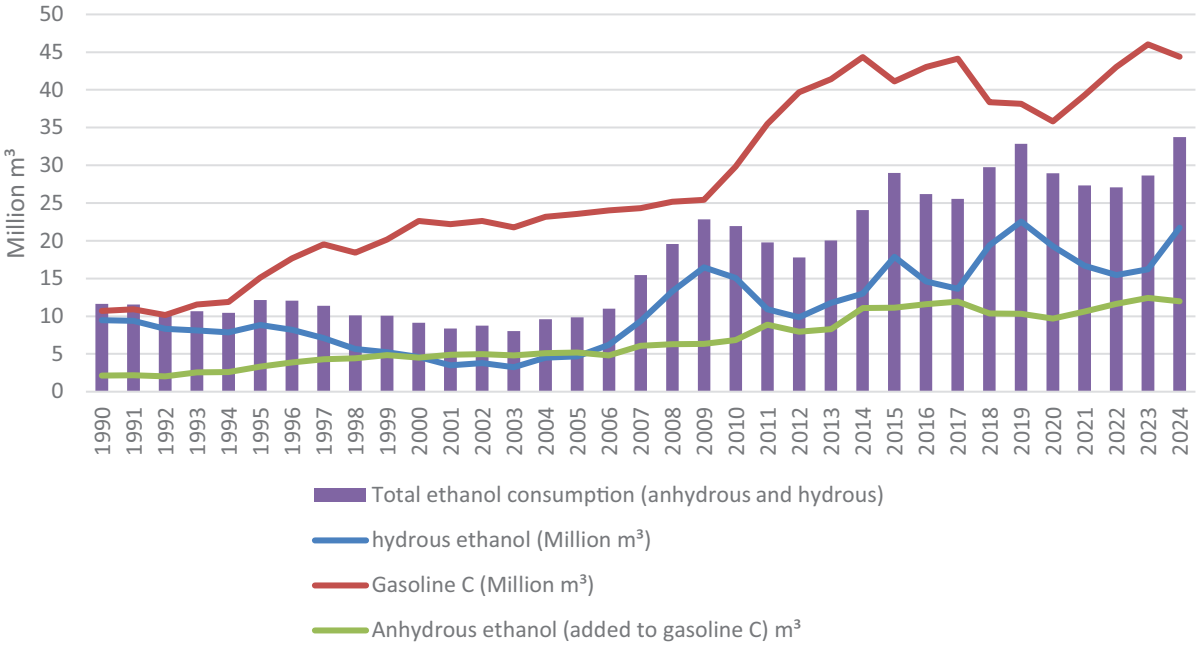

FIGURE 3 | Consumption (domestic sales to distributors) of Gasoline C (containing amounts of anhydrous ethanol), hydrous ethanol (E100), and anhydrous ethanol (added to gasoline), in m^3. *Source:* Prepared by the authors based on data from ANP [9]. Calculation of anhydrous ethanol based on the evolution of mandatory blending mandates of anhydrous ethanol in Gasoline C sold in Brazil, which varied from 20% to 27.5% from the first phase of Proalcool until 2024.

Figure 3 shows Brazil's domestic consumption of Gasoline C (containing anhydrous ethanol blend), hydrous ethanol, and anhydrous ethanol.

Amid this period of growth and crisis, significant advancements in harvest mechanization occurred, primarily motivated by environmental restrictions. Noteworthy is Federal Decree No. 2661, dated 07/08/98 and the signing of an environmental protocol between the Brazilian Sugarcane Industry Association (UNICA) [10] and the São Paulo State Government, further advancing the elimination of sugarcane burning in São Paulo State.

As manual cutting of raw sugarcane became less productive per worker, mechanization increased, making sugar and ethanol production less labor intensive. In the 2024/2025 sugarcane crop, mechanical harvesting represents 92.4% of the national production [1]. All regions of the country exhibit mechanization rates equal to or close to 100%, with the exception of the Northeast, where the rate stands at 27% [1].

Despite the advantages associated with improved working conditions due to the reduction in manual cutting, this transition led to a decrease in the labor demanded over the years. Although sugarcane production in tons increased by 18.4%

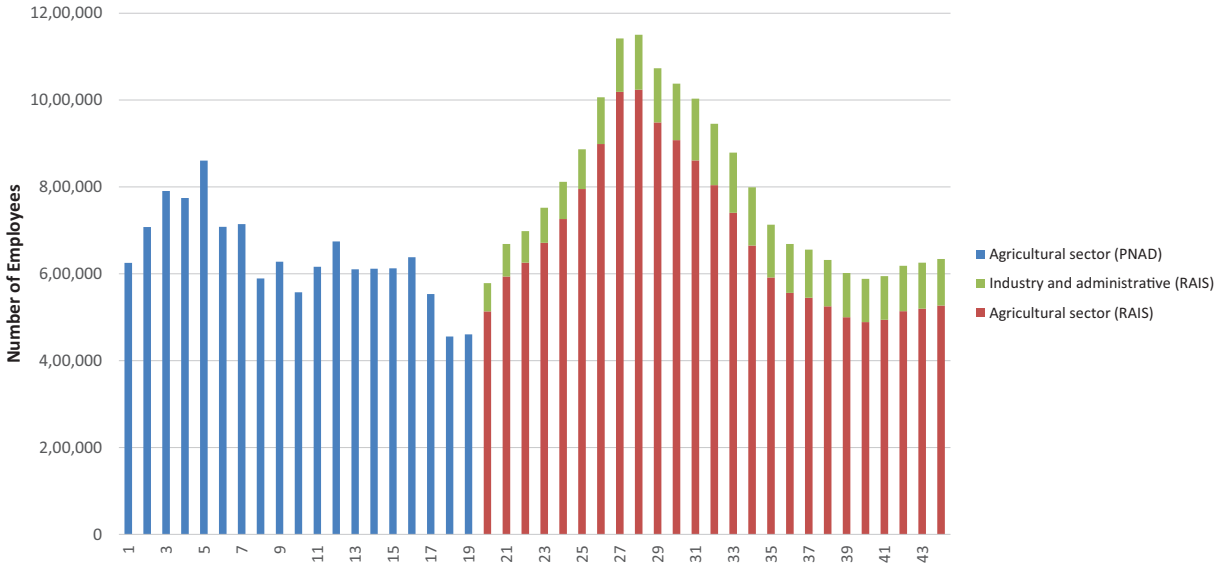

FIGURE 4 | Evolution of the number of formal workers in Brazil in the agricultural and industrial/administrative sectors of the sugarcane industry. *Source:* Prepared by the authors based on data from PNAD (2025) [11] and RAIS (2025) [2]. The National Household Sample Survey (PNAD), conducted by the Brazilian Institute of Geography and Statistics (IBGE), provides data on both formal and informal sectors of the Brazilian labor market. Due to its sampling nature, PNAD is limited in supporting analyses requiring higher levels of disaggregation. For this reason, PNAD data are utilized up to the year 2000, a period during which informality in the sector represented approximately 30% of workers. From 2000 onwards, RAIS data (employment data from the Brazilian Ministry of Labor) are prioritized, as informality in the sector declined to approximately 10% starting in 2015. Additionally, the use of RAIS enables a more accurate assessment of the number of workers in the sector allocated to industrial and administrative activities. The classification of workers across activities was conducted using the Brazilian Classification of Occupations (Classificação Brasileira de Ocupações—CBO) from formal employment records.

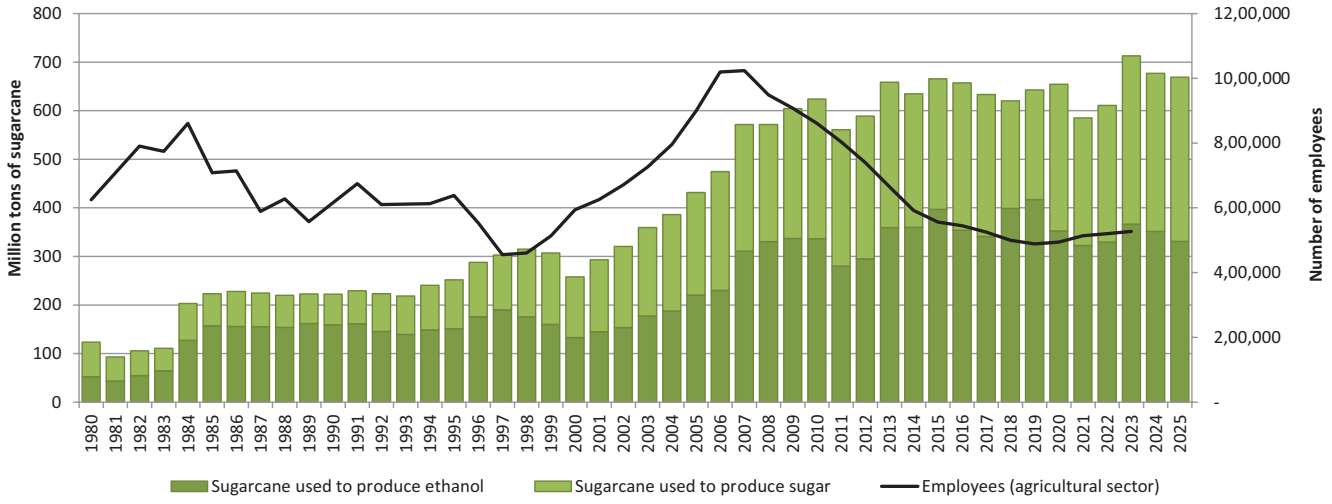

FIGURE 5 | Sugarcane production in tons and its allocation for sugar or ethanol production, 1980–2024. *Source:* Prepared by the authors based on data from CONAB [1]; UNICA [10]; PNAD [11]; RAIS [2].

between 2008 and 2024, the number of formal jobs in the sugarcane agricultural sector decreased by 48.5% over the same period, with greater job stability observed from 2016 onwards, when the mechanization process was already consolidated—Figures 4 and 5.

3 | Sugarcane Workers Conditions Overview

The literature on the social conditions of sugarcane harvesting during the 1980s was highly critical, consistently highlighting concerns about poor working conditions associated with manual harvesting practices. Issues such as productivity-based payment systems (where higher cane cutting yields resulted in higher earnings), health problems, worker migration, and substandard housing dominated discussions [12, 13]. Although significant improvements in working conditions were achieved during that period, there remained substantial room for progress [13].

Cardoso et al. [14] emphasized the physical needs of manual sugarcane cutting, describing this work as exhausting due to

repetitive movements, long working hours, high exposure to sunlight, and heavy loads. Similarly, Moreira and Goldenberg [15] found that while employment relations in the sugarcane sector were relatively better compared to other rural sectors, localized issues persisted at that time. Their study revealed that despite ongoing intensified labor inspections in the sugarcane sector, these efforts were insufficient to eliminate reported violations of workers' rights.

Martinelli and Filoso [12] addressed environmental and social challenges surrounding ethanol production; mounting pressure from Brazilian authorities and the international community led the ethanol industry to acknowledge the contradiction of promoting ethanol as a clean and sustainable energy source while workers continued to face adverse conditions and inadequate wages.

Capitani et al. [16] highlighted disparities between studies employing well-established analytical models with access to official socioeconomic data and those focusing on labor irregularities in rural areas. They utilized official labor inspection data from mobile groups associated with Brazil's Ministry of Labor and Employment (MTE) and noted a decline in labor irregularities in the sugarcane industry, which was undergoing changes to align its labor practices with existing laws and regulations. Labor inspections revealed that less than 1% of workers faced adverse conditions or penalties. Their results, alongside broader literature data, demonstrated notable improvements in labor indicators within the sugarcane industry, including increased formal agricultural employment, higher wages, job growth in new areas, and advancements in education, age, and gender distributions [16].

Kokol and Misailidis [17] strongly criticized the labor conditions of sugarcane cutters in Sao Paulo during that time. However, the authors acknowledged the complexity of the issue, arguing that while sugarcane plantation work posed significant challenges to workers' rights, mechanization had the potential to result in widespread unemployment. They also highlighted federal government initiatives, collaborations with trade unions, and private sector efforts, such as the National Commitment to Improve Working Conditions in Sugarcane, the Renewal Project led by agro-industrial companies and the Inter-American Development Bank (IDB), along with MTE initiatives. Despite these measures, the authors expressed doubts regarding their effectiveness, citing persistent precarity, low wages, and limited education among workers at that time.

Since the mid-2000s improvements in the labor market of the sugarcane agroindustry have been observed. The notable reasons cited in the literature include: greater enforcement of the existing labor legislation; adherence to certification standards; the entry of foreign capital in the sugar and ethanol sectors; the growing international attention to national labor practices and the adoption of mechanized harvest [18, 19].

Furthermore, Brazil's growing sugar exports prompted competitors like the European Union to claim its lower costs stemmed from environmental damage and poor labor practices. Although these were not Brazil's actual cost advantages, such criticism motivated producers to adopt best practices and pursue certification of the production [18, 19].

3.1 | Employment Data in Agriculture and Sugarcane Industries

Several authors have previously analyzed the characteristics of the workforce, pay and working conditions [5, 20–30]. Since 2003, average earnings in Brazil's sugarcane sector have surpassed those in general agriculture, reversing the trend seen in the 1990s [21, 27–29]. The average years of schooling for workers in sugar cane have proven to be higher than those in agriculture in general since 2005. As the sector shifts toward more advanced technological practices, it demands labor with higher skill levels [27, 29, 30].

Socioeconomic indicators like education, job formalization, and wages are higher in Center-South region, more specifically in Sao Paulo state, than in the North-Northeast. To examine wage differences associated with age, sex, schooling, region, occupational group, wealth variables, union affiliation, among other variables, several researchers have estimated *Earnings Equations*.

In the majority of this literature, education is seen as the main income determinant, and the literature consistently highlights that women earn lower wages and that earnings are regionally influenced, with workers in the North-Northeast earning less, likely due to lower economic development in these regions. These effects on income were captured by several authors [21–25, 28–31].

Moraes et al. [26] analyzed socio-economic indicators for the sugarcane and agricultural sectors, including literacy, education, wages, employment, and contract types, as well as the role of family by comparing first and second-generation sugarcane workers with agricultural sector workers. Their findings demonstrated that between 2000 and 2012, formal jobs in these sectors grew by 69.8%, driven by increased production. However, employment in the sugarcane sector dropped by 7.4% (due to sugarcane mechanization), while ethanol plants and sugar mills saw significant growth of 205.2% and 153.9%, respectively.

The authors also noted that the second generation of workers showed advancements in education, opportunities, and working conditions. In 2012, agricultural workers averaged 4 years of schooling, while those in the sugarcane sector had slightly higher schooling at 5 years. For their offspring, sugarcane workers' children averaged 8.4 years of schooling, compared to 8.1 years for agricultural workers' children. Additionally, the proportion of illiterate offspring or those with only up to 4 years of education was lower in the sugarcane sector (12.3%) than in general agriculture (17%) [26].

Sugarcane workers also earned 45% higher wages on average compared to the broader agricultural workforce. Descendants of sugarcane workers earned nearly 29.9% more than those from other agricultural sectors. Formal employment, which guarantees basic labor rights, was much higher in the sugarcane sector (87% in 2012) than in the general agricultural

sector (34.2%). São Paulo, the largest sugarcane-producing state, had over 156,000 formally employed sugarcane workers, representing more than 90% of the sector's total formal jobs. Among offspring working in the sugarcane sector, 70% had formal employment, compared to 49.3% in other agricultural sectors [26].

Formal employment in the sugarcane sector positively influences the likelihood of offspring working under similar conditions, leading to better education, higher wages, and increased formal employment rates compared to other agricultural sectors. Regarding occupational mobility, 43.2% of agricultural workers' descendants remained in the agricultural sector, with the service sector being the next most common. For sugarcane workers' offspring, only 29.3% remained in agriculture; 35.3% transitioned to the service sector, and 20.9% moved to the industrial sector, indicating greater mobility to other fields compared to descendants of general agricultural workers [26].

The following section highlights the impacts of harvesting mechanization on jobs in the sugarcane industry.

3.2 | Mechanical Harvesting and Migration of Workers

Banning the burning of sugarcane fields sped up agricultural mechanization in the main producing states. Although the benefits to the environment are undeniable, it has caused a significant reduction in jobs (as seen in Section 2), especially among low-skilled workers.

Harvest mechanization accelerated in the Center-South region for reasons beyond the ban on sugarcane burning. Sugar and ethanol plants use sugarcane bagasse and straw to co-generate electricity. The electricity generated can be used both inside the plant as well as to sell energy on the market, an advantage that would be lost with sugarcane burning.

Several authors highlighted the increased demand for skilled, educated workers, while reducing jobs for low-schooled employees. This demand creates opportunities for tractor operators, drivers, mechanics, harvester drivers, electronics technicians, among others, and it reduces, at a higher percentage, the demand for low-skilled workers, driving them out of the field [27, 29–36].

Baccarin, Gebara, and Borges [33] analyzed the period from 2007 to 2009, and also point to a trend of reduced employment seasonality in plantations, even for unskilled workers. On the other hand, there was inevitably a decrease in job opportunities for many sugarcane cutters, often lacking education and professional experience in other areas [24, 27, 33].

Cardoso et al. [32] evaluated manual and mechanized sugarcane harvesting in São Paulo, Northeast, and Center-West regions using Engineering Economics, Life Cycle Assessment, and Social Life Cycle Assessment metrics. In accordance with the literature, they found that manual harvesting results in greater job creation, whereas mechanized sugarcane systems are associated with improved working conditions and higher average incomes for workers, but demand skilled labor and greater investment in machinery.

These findings are consistent with those reported by Postal et al. [30], who examine the multifaceted impacts of sugarcane expansion in Brazil by assessing local stakeholders' perceptions across 33 municipalities in the Center-South region. Based on primary data from 353 interviews, the authors find a generally positive level of local acceptance of the sector, particularly with respect to economic and social dimensions; respondents emphasize job creation, income generation, and improvements in working conditions [30].

The analysis of employment data from RAIS (Administrative Records of Social Information) of Brazil's Ministry of Labor [2] illustrates this effect highlighted in the literature. Table 1 presents the evolution of the number of workers in the sector (sugarcane production and sugarcane processing industry for sugar and ethanol production) by years of education and average wage, comparing the sector's labor market in 2008 (beginning of mechanization intensification) and 2016 (consolidation of the process).

It can be observed that the reduction in the number of jobs between 2008 and 2016 was mainly concentrated among workers with at most 5 years of education and decreased also for the category of 6–9 years of education. Conversely, there was even an increase in the number of workers with 10 or more years of education, associated with the highest average salaries. These data indicate a shift in the workforce profile of the sector driven by environmental requirements and consequent harvest mechanization.

Using the RAIS microdata database (previously referenced) to evaluate the reallocation of workers from the sugar-energy sector following the decrease caused by mechanization reveals significant labor market challenges overall. It is observed that, among those employed in the agricultural activities of the sugar-energy sector in 2008, 58.1% were no longer engaged in formal employment by 2016. This percentage is significantly higher compared to industrial and administrative activities within the sector during the same period (approximately 30%). This finding

TABLE 1 | Evolution of the number of employed persons and the average salary in Brazil by range of years of study for 2008 and 2016.

Years of schooling	Number of employees		Real wage*	
	2008	2016	2008	2016
Illiterate	99.925	38.876	319.5	388.41
1-5	610.853	248.294	430.5	521.9
6–9	329.496	211.846	503.1	658.8
10–12	211.693	252.306	622.5	773.2
More than13 years	31.291	43.589	2016.5	1923.4
Total of Workers	1.283.258	794.911		

*Values in Brazilian reais deflated by the price index (IPCA) and converted to November 2017 US dollars.
Source: Prepared by the authors based on data from RAIS [2].

is relevant as it highlights the greater difficulties faced by agricultural sector workers with lower education levels in reintegrating into the formal labor market.

Despite initiatives by major companies in the sector to promote training and reintegration programs for these workers in different roles, as evidenced by Baccarin, Gebara, and Borges [33], these impacts proved to be highly limited, given the substantial reduction in the number of jobs within the sector. Evaluating RAIS data, among agricultural workers who remained active in the formal labor market in 2016 (41.9% of the total), only 8.9% transitioned to other activities within the sector (industrial or administrative activities), while 49.8% migrated to other sectors.

Cardoso et al. [32] assessed three social effects in the sugarcane production systems: the total number of jobs created, the number of occupational accidents, and the average wage of workers, considering manual and mechanical technologies for planting and harvesting. Manual cutting improves employment rates, while mechanized harvesting leads to safer jobs (less occupational accidents) and higher wages. Mechanization in rural regions can result in reduced employment opportunities; however, this effect may be offset by increased and improved job prospects in sectors related to machinery and agricultural inputs [33].

With respect to migration, each year thousands of workers from Brazil's less economically developed regions traditionally used to migrate to the state of São Paulo during the harvest season to participate in the manual sugar cane harvesting.

Moraes, Figueiredo, and Oliveira [35] carried out field research to clarify what drives migration, examine its effects on both origin and destination cities, and assess how workers view the rise of mechanized sugarcane harvesting. The results indicate that many sugarcane harvesters with limited education are likely to keep migrating for improved living conditions. The study recommends public policies to create jobs in migrants' home regions to offset job losses from reduced sugarcane manual harvesting.

Moraes, Figueiredo, and Oliveira [36] examined the migration patterns of sugarcane cutters from economically disadvantaged regions of Brazil to the State of São Paulo. They compared the socioeconomic profiles of specialized and non-specialized workers and examined how environmental legislation affects non-specialized employees' wages. The Differences in Differences fitted equation indicated that the environmental law impacted the wages of unspecialized workers. It clearly seems the importance of local public policies to improve schooling and to create job opportunities there.

Upon analyzing data from the RAIS database [2] covering the period from 2008 to 2016, results revealed that 46.43% of workers exiting the sugar-energy sector who remained employed in the formal labor market migrated to a different federal state within Brazil. The migration patterns exhibit considerable dispersion across states, without a well-defined migratory trend. Notably, the highest observed migration flow occurred from Minas Gerais to São Paulo, accounting for 7.1% of the total migrant workforce.

3.3 | Economic Impacts of Brazilian Sugarcane Industry

There is evidence that the existence of a sugarcane agroindustry could lead to economic growth by creating jobs and increasing income, generating positive net benefits—especially for Brazil's low-income population. Recent studies have further elucidated the economic impact that establishing an ethanol plant has on both the municipality's economic growth and development, as well as on adjacent regions. Multiple methodologies exist for assessing the impacts.

Conversely, case studies found that many of the jobs generated were unstable, exposing rural workers to health hazards and leaving immigrant workers in inadequate housing, which highlights negative effects at the local level. The literature review finds that case studies give detailed context; however, they cannot fully explain the sugarcane industry's expansion because of differences in institutions, economies, and societies across regions.

The jobs generated by the sector include those directly involved with sugarcane, sugar, and ethanol production, as well as positions created through the sector's interactions with other parts of the economy. These interactions may involve purchasing inputs for production, supplying goods for indirect use, or providing products for direct consumption by end users of sugar and ethanol.

In this review we will present the recent papers that adopt the following methods: Econometrics, General Equilibrium Models, and Input–Output Models to assess the impacts of the sugarcane industry.

3.3.1 | Econometrics

Deuss [37] used propensity score matching method to assess how sugarcane industry expansion affected economic development across Brazil and in its main producing regions: the North-Northeast (NE) and Center-South (CS). The effects are examined at the municipality level. The results indicate that municipalities in NE and CS saw economic growth in Gross Domestic Product (GDP) from increased sugarcane production, while SP showed no notable effect.

Martinelli et al. [38] analyzed how rural development in São Paulo relates to sugarcane, ethanol, and cattle production. Their results suggest that the value-added components of sugarcane production, like sugar refining and ethanol production, may have a strong positive effect on local human development in comparison to primary agricultural production activities and other land uses.

These findings suggest that developing a local sugarcane processing industry can boost rural development. The link between various socioeconomic indicators and the presence of sugar mills in São Paulo's municipalities shows that the sugarcane industry boosts jobs, public services, and infrastructure. The authors conclude that the social benefits resulting from the expansion of sugar and ethanol production in São Paulo over the past decade—as evaluated through human development indicators and income distribution—are greater than is commonly recognized, particularly in comparison to cattle ranching [38].

Moraes, Caldarelli, and Gilio [18] examined the socioeconomic effects of expanding sugarcane, sugar, and ethanol production in São Paulo municipalities from 2005 to 2009, using FIRJAN's Municipal Development Index (IFDM) as a proxy for HDI. They use both panel data and quantile regression (that better allows to address the effects on different levels of development municipalities) to assess socioeconomic impacts across municipalities with varying development levels. The results show that municipalities with sugar/ethanol plants and sugarcane areas have both IFDM indexes higher than municipalities without sugar and ethanol production. Processing sugarcane plants (for ethanol or sugar) have had a greater effect on development indexes than sugarcane production alone. Quantile regression results show that industry affects municipalities with low and medium development more than those with higher development. They conclude that the sugarcane industry improved the regional development index for the municipalities of the state of São Paulo in the analyzed period.

Gilio and Moraes [39] assess the socioeconomic development impacts of the sugarcane industry expansion on the 650 municipalities in the Brazilian state of São Paulo for the 2005–2011 period. The aim was to determine the relationships between the sector's expansion (considering both the sugarcane areas and the presence of the processing plants) and the Municipal Development Index (IFDM), provided by the Federation of the State of Rio de Janeiro Industries (FIRJAN). Both intra and inter-municipality activities were addressed. The method used is a dynamic spatial panel model with the System Generalized Method of Moments (GMM-SYS). Results indicate that the presence of sugarcane processing plants brings considerable direct (in the municipality) and indirect (in the neighborhood) socio-economic benefits to the population. The overall positive socioeconomic impacts demonstrate that the sugarcane industry contributes significantly to both local and regional economic activity. Its presence stimulates direct employment and income within the sector, as well as indirectly supporting growth in associated activities. They found a small negative relationship between increases in the amount of area devoted to sugarcane cultivation in a municipality and the IFDM value for that municipality, which they explained by job losses in the farming sector, most likely due to the recent mechanization process of sugarcane harvesting.

Moraes, Bacchi, and Caldarelli [40] examined how the rapid expansion of Brazil's sugarcane, sugar, and ethanol industries between 2000 and 2008 affected municipal Gross Domestic Product (GDP) per capita in the south-central region. They used the Generalized Method of Moments System estimator and a spatial dynamic panel data. The results demonstrate that sugarcane production exerts a significant and positive influence on municipal GDP per capita, both within the municipalities directly involved in production and in adjacent municipalities as well. Cumulative direct and indirect effects raised real municipal GDP per capita by $1028 in host municipalities and by $324 in each of their 15 nearest neighbors. The effects of establishing a sugar mill or ethanol plant are most significant for the host municipality and persist for at least 10 years after operations begin.

Satolo and Bacchi [41] analyzed the impact of sugarcane and ethanol expansion in the state of São Paulo, assessing their impact on GDP per capita of different municipalities through a spatial dynamic panel data model. They found that the effect of the expansion of the sugarcane industry is positive on GDP per capita if this expansion occurs in an area of up to 23% of the municipalities' agricultural areas, replacing crops or pasture areas. They also noticed a positive impact on the sugarcane industry's presence on the nearby municipalities, although it was a small effect. According to the authors, the spillover effect may be attributed to factors such as migratory attraction and growth in local income, both of which stimulate demand for locally consumed goods and services, thereby amplifying the positive impact on income.

Bacchi and Caldarelli [42] conducted a panel data analysis to assess the externalities associated with the growth of the sugarcane industry, using the Municipal Development FIRJAN Index (IFDM) as an evaluative metric. They show that sugarcane industry expansion in São Paulo boosted jobs and income but did not significantly improve health or education indicators.

Machado et al. [43] used panel data modeling to assess the socioeconomic effects of sugarcane production in three regions: Piracicaba, Presidente Prudente, and Southwest Goias, Brazil. Local quality of life was characterized by five key dimensions: income and inequality, education, infrastructure, health, and overall development. Sugarcane production in President Prudente reduces poverty, improves education, and helps develop the microregion. The city shows the highest progress levels. Southwest Goias, where sugarcane operations started later, is the only microregion where the adjusted models show no significant variables related to the sugarcane sector. In general, sugarcane brings positive relationship, or no relationship at all, as it is the case of health indicators. On other crops and how they relate to quality of life.

Walter et al. [44] examined bioethanol sustainability by assessing direct land use change, GHG emissions, and socio-economic factors, focusing on sugarcane and ethanol production in Sao Paulo and Mato Grosso. Positive socioeconomic impacts were seen in São Paulo municipalities, where most production occurs; these benefits mainly result from increased economic activity. Overall, they found that a substantial portion of ethanol production in Brazil demonstrates sustainability across the three evaluated dimensions. However, significant differences in production conditions prevent broad generalizations of these findings.

Tomei et al. [45] investigated the association between the existence of sugarcane processing mills and human development indicators at the municipal level in Mato Grosso do Sul. They developed a method drawing on UN Human Development Index and the Social Responsibility Index of Sao Paulo. The paper finds evidence that municipalities with a mill perform relatively better in terms of human development than those without.

Sparovek et al. [46] analyzed the expansion of sugarcane cultivation in Brazil between 1996 and 2006, a period marked by significant growth. They examined the environmental, land-use, and economic effects of sugarcane expansion. They conclude that, overall, the expansion of sugarcane was not a direct driver of deforestation within the traditional agricultural region where most of this growth occurred. Additionally, the expansion did

not notably impact food crop production during the study period. With respect to the impacts on local economies, the authors found that within the Central Area of Expansion (CEA), Municipal Gross Domestic Product (MGDP) in 2006 was higher in regions experiencing significant sugarcane expansion compared to regions with non-significant expansion. Moreover, within the CEA, municipal gross domestic product grew at a higher rate, which suggests that sugarcane expansion may contribute to economic growth through both increased agricultural activity and local industrialization.

3.3.2 | General Equilibrium Models Simulation

Ferreira Filho [27] examined the social consequences of Brazil's expanding ethanol industry on labor demand, income distribution, and poverty. He verified how the sugarcane and ethanol production growth was reshaping patterns of labor demand. Simultaneously, the distributional effects of sugarcane expansion, along with its impacts on food security and land use change, were assessed using general equilibrium simulation models.

The results show that sugarcane production in Brazil had higher average earnings and years of schooling than general agriculture, correlating with increased production in the Southeast and Central-West regions, whose production is more capital intensive and yields higher productivity than in Northeast Brazil's traditional regions. He concludes that the expansion helped raise average earnings in agriculture, which is the sector where most poverty in Brazil occurs. Moreover, it does not have a negative effect on poverty and has only minor impacts on food prices. He pointed out social challenges linked to regional aspects because the expansion was supposed to occur in Brazil's wealthiest areas and away from the poorer Northeast.

3.3.3 | Input–Output Matrix

Brinkman et al. [47] analyzed how increasing ethanol production affects GDP, employment, and trade, noting that these effects differ across various regions of the country and among income groups. The findings indicate that the projected expansion of sugarcane ethanol production in Brazil by 2030 may result in a $2.6 billion increase in national GDP and generate approximately 53,000 additional jobs. Additional employment is primarily generated in lower-income classes. Sugarcane expansion generally brings more benefits than drawbacks from decreased crop and livestock production at the microregional level. Significant variations in impacts were observed among the regions, which can be attributed to differences in the structure of the local economies.

Martinez et al. [31] evaluated the value added, imports, and employment effects of sugarcane ethanol production in Northeast Brazil. An extended inter-regional Input–Output (IO) model is used to analyze three scenarios projected for 2020. In all scenarios, value added and imports increase compared to the current situation. The loss of 114,000 jobs from manual harvesting being replaced by mechanical may be balanced by increased production and indirect benefits. The indirect effects of sugarcane production in the NE are large in the rest of Brazil due to the import of inputs from these regions. They conclude that expanding the sugarcane–ethanol industry can lead to substantial socioeconomic benefits, both within the NE region and across the broader Brazilian economy.

Costa et al. [48] used the inter-regional Input–Output Matrix for Brazil's North-Northeast, Center-South, and São Paulo to estimate job impacts from replacing gasoline C with hydrous ethanol. Simulating ethanol consumption increases of 5%, 10%, and 15% over gasoline C could create 39,234, 78,467, and 117,701 new jobs, respectively. Remuneration increased by approximately R$ 79 million, R$ 157 million, and R$ 236 million, respectively for the same scenarios. The findings indicate that shocks originating from the North-Northeast region were responsible for over half of the effects on employment and approximately 40% of the impacts on wages.

4 | Discussion and Conclusions

Brazil is internationally recognized as a pioneer in sugarcane ethanol production and utilization, with 50 years of expertise in employing it as a fuel source.

The literature emphasizes several advantages in sugarcane ethanol production and usage, such as foreign exchange savings by reducing oil imports, fostering technological development, minimizing greenhouse gas emissions, generating employment and income, and driving economic growth. This comprehensive review focuses on the following socioeconomic topics: employment data, working conditions, the impacts of mechanized harvesting, and broader socioeconomic implications. The accessibility of official socioeconomic data series enables a comprehensive analysis of the Brazilian experience from various perspectives.

In the 1980s, the literature often criticized the poor conditions of manual sugarcane harvesting, highlighting issues such as productivity-based pay, health risks, worker migration, and inadequate housing.

However, since the mid-2000s, Brazil has made significant advancements in the sugarcane labor market. This progress was driven by stricter enforcement of labor laws, the implementation of certification standards, the entry of foreign multinational companies into the sector with better labor practices, global scrutiny from competitors in the sugar industry, and the introduction of mechanized sugarcane harvesting. These improvements have led to noteworthy benefits, including more formal employment opportunities, increased wages, and improved working conditions.

Regarding literacy rates, educational attainment, wages, employment rates, and formal labor—both within the sugarcane sector and compared to the agricultural sector overall—indicators for sugarcane sector workers are superior across all dimensions.

Moreover, studies suggest that descendants of sugarcane workers tend to achieve stronger socioeconomic outcomes and

pursue more skilled professions compared to other agricultural workers.

Employment creation within the sugarcane, sugar, and ethanol sectors is also noteworthy. According to data from Brazil's Annual Social Information Report (RAIS) by the Ministry of Labor, 749,930 workers were formally employed in these three sectors in 2024, with the sugarcane sector (agricultural production phase) accounting for 526,929 workers.

The mechanization of sugarcane fields, particularly in Brazil's Center-South region, has led to a significant reduction in the number of workers in the agricultural sector. However, it has also produced favorable outcomes for job quality, such as increased formal employment, higher average wages, and improved working conditions. Socioeconomic impacts of the sugarcane agroindustry are evaluated through various methodologies, with the literature indicating its capacity to stimulate economic growth by generating employment and income, yielding positive net benefits—especially for low-income populations in Brazil.

Ethanol plant establishments are shown to contribute to economic development both within municipalities and neighboring regions, driving broader economic activity directly through employment and income generation as well as indirectly by stimulating related sectors. Additionally, studies have demonstrated improvements in regional development indices, particularly in municipalities within São Paulo and other regions, emphasizing the sugarcane industry's role in local and regional growth.

Beyond widely recognized environmental benefits, the production of sugarcane ethanol also enhances socioeconomic indicators, especially in municipalities with low to medium development levels. Considering that rural areas of Brazil generally have lower socioeconomic indicators compared to urban regions, these findings support the formulation of public policies aimed at fostering social and economic progress. These results highlight the importance of integrating and considering socioeconomic factors in energy policies, particularly in the context of global transitions to renewable energy and biofuels. Brazil's over 50 years of experience with incentive policies, such as the Proálcool program, and their effects offer valuable lessons to the world, especially at a time when bioenergy is emerging as a solution in new areas beyond first-generation fuels, such as sustainable aviation fuel (SAF), maritime transportation, and green hydrogen production.

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Conflicts of Interest

The authors declare no conflicts of interest.

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