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BIOMASS ENERGY AND THE OPPORTUNITIES OF MAIZE AND SORGHUM: RAW MATERIALS, BIOETHANOL, CO-PRODUCTS, AND A NEW LOGIC FOR BIOREFINERIES IN THE INTERIOR OF BRAZIL.

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ABSTRACT – The transformation of the Brazilian energy and agro-industrial landscape, starting with the second maize and sorghum harvest, goes beyond the production of biofuels. This study analyzes the expansion of bioethanol production from grain starches in Brazil, with a central focus on the second crop of maize and sorghum. The objective is to investigate how these crops, more than just producing raw materials for the biofuel industry, consolidate a new logic of multi-product biorefinery in the interior of the country, integrating energy production with food security and regional development. The methodology is based on the analysis of value chains, with an emphasis on the transition from the flexible plant model to units dedicated to grain processing. The results indicate that utilizing these raw materials allows for the decarbonization of the transportation matrix and, simultaneously, generates co-products of high nutritional value, such as the distiller's dried grains (DDG), wet distillers grains (WDG) and distiller's dried grains with solubles (DDGS). It is concluded that this integration strengthens animal protein supply chains and establishes a circular economy model that optimizes logistics and adds value to national agricultural production, positioning biorefineries as strategic hubs for consolidating Brazil's sustainable and competitive bioeconomy. The study also demonstrates that the food-energy nexus has undergone transformations, shifting in the 2000s from a critical dilemma of choosing between producing food or producing energy, to a modern and disruptive model of agro-industrial competitiveness, with the sustainable production of food and energy in Brazilian biorefineries.

Security and sustainability in the context of climate change and energy transition require the integration of strategies for leveraging natural resources and human intelligence for a robust tropical agricultural bioeconomy. This model is heavily based on science, data, and evidence, seeking competitive advantage by promoting the development of solutions that increase the productivity and climate resilience of production systems, and strengthening a diversified bioeconomy that ensures the country's long-term food and energy security.

In this context, energy sources, new raw materials derived from biodiversity, and conversion and transfer processes in biophysical-chemical systems create and demand new concepts of utility for competitiveness and sustainability. These concepts involve the conversion of organic matter (biological raw materials and agricultural, forestry, and urban waste) into electricity, heat, or biofuels (ethanol, biodiesel, biogas, biomethane, and similar products) through processes such as fermentation, enzymatic hydrolysis, combustion, gasification, pyrolysis, or anaerobic digestion, taking advantage of the natural carbon cycle to obtain a renewable and sustainable source, reducing the volume of waste and decreasing dependence on fossil fuels.

The conversion of radiant energy into chemical energy occurs in processes such as photosynthesis, carried out by plants and some bacteria. In this process, light (radiant) energy is captured and used to convert carbon dioxide and water into glucose (a carbohydrate that stores chemical energy) and oxygen. This is the main process by which the Sun's energy enters the Earth's food chain.

The cultivation of second-crop maize and sorghum in the interior of Brazil offers vast opportunities for the bioeconomy, serving as versatile feedstocks for producing bioethanol, generating energy from biomass, and producing high-value co-products such as proteins for animal feed. This supports a new logic of integrated and sustainable biorefinery.

Maize and sorghum, second-crop grains, are planted after the soybean harvest, adapting well to water deficit conditions and shorter planting windows.

Raw materials: Grains are the main source of starch for ethanol production, while the aerial parts (straw, stalk) constitute lignocellulosic biomass that can be used for thermal or electrical energy generation. Biomass sorghum, a specific type, is cultivated to maximize plant biomass production for energy generation.

Co-products: Processing maize and sorghum for ethanol production yields valuable byproducts. The main one is DDG, a bran rich in protein (25-30%), fiber, and amino acids, widely used in animal nutrition, replacing maize and even soybean meal in diets for poultry, swine, and cattle.

Bioethanol from Starchy Grains

Ethanol production from maize starch has grown exponentially in Brazil, accounting for approximately 20% of national production in 2024, diversifying the energy matrix that previously depended almost exclusively on sugarcane (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2025a; Conab, 2025a; Targueta et al., 2025). Grain sorghum also shows promise for ethanol production, with potential for use in existing sugarcane mills or dedicated plants. The technology to produce second-generation (2G) ethanol from cellulosic biomass is also being researched by Embrapa, optimizing the production process through the integral use of the plant.

Protein Value Chains

The integration of ethanol production with livestock farming is one of the key points of this new logic. The DDG generated in maize and sorghum ethanol plants creates a local protein value chain. Sorghum also naturally has a slightly higher crude protein content than maize (8.5-9% versus 7.8-8%). This strengthens livestock nutrition in the Brazilian Midwest, reducing dependence on external sources and optimizing regional logistics.

New Logic for Biorefineries in the Interior of Brazil

The "new logic of territorial biorefinery" in the interior of Brazil is based on integration and the circular economy, and includes the availability of raw materials, industrial facilities and conversion processes (physico-chemical and biological), and production mechanisms, energy support, and infrastructure and logistics for product distribution to domestic and international markets. Agroenergy is a typical economic activity of public-private alliances and partnerships, and a future-oriented premise considers "producing and consuming locally/regionally" relevant, using existing agricultural inputs (water, soil, energy, organisms, nutrients, carbon), infrastructure and logistics, markets, etc., or those that can be accessed from the local/regional location. The plants (dedicated and flexible) process maize and sorghum grains into ethanol, using plant biomass and, when applicable, complementary raw materials to generate their own thermal energy and surplus electricity (cogeneration), and produce DDG as a valuable co-product for animal feed.
This approach offers:

Sustainability: Efficient use of resources, waste reduction, and decreased pressure on native ecosystems, such as the Caatinga, where firewood is used as an energy source.

Flexibility and Energy Security: Diversification of raw materials (maize, sorghum, sugarcane), mitigating climate and market risks.

Regional Development: Generating jobs and income in agriculture and industry, with the consolidation of agro-industrial production hubs in regions such as Mato Grosso.
In short, second-crop maize and sorghum are cornerstones of a more robust, efficient, and sustainable agro-industrial development model for biomass energy production in Brazil, optimizing land use and integrating different production chains.

The Paradigm Shift in the National Energy Matrix

The history of biofuels in Brazil is currently at a turning point comparable to the launch of the Proálcool program in the 1970s. For almost half a century, the identity of Brazilian ethanol was inseparable from sugarcane, a crop that shaped not only the energy matrix but also the socioeconomic organization of vast regions of the country, notably the coastal Northeast and the interior of the state of São Paulo. However, the last decade has witnessed the silent, yet overwhelming, emergence of a new industrial vector that is reshaping the economic geography of the Central-West region: grain ethanol, primarily based on second-crop maize and, more recently, on the strategic crop of sorghum (Produção […], 2025).

Unlike traditional sugarcane mills, subject to seasonal harvests and industrial idleness during the off-season, the new grain ethanol industry operates under the logic of a continuous flow biorefinery. These industrial plants, operating 365 days a year, transcend the classic definition of "fuel producers." The plants establish themselves as complexes for converting starch into multiple forms of energy and bioproducts: liquid biofuels (anhydrous and hydrated ethanol), electric energy (bioelectricity), high-protein animal feed (DDG/WDG), vegetable oil, and, at the technological frontier, biomethane and biogenic carbon dioxide for industrial use or geological capture (União Nacional do Etanol de Milho, 2026a).

The following analysis details how maize production, driven by the agronomic technology of the "safrinha" – cultivation carried out immediately after the soybean harvest, in the same area and in the same agricultural year – generated a surplus of biomass that enabled industrialization in the interior of the country. It addresses the intrinsic sustainability of this model, which dissociates the increase in energy production from the need to expand the agricultural frontier, neutralizing the classic "food versus fuel" debate and mitigating the risks of Indirect Land Use Change (ILUC) (Gazzoni, 2014; FS Bioenergia, 2026). Furthermore, it investigates the emerging role of sorghum as a climate resilience crop and the necessary logistical infrastructure – from railways to pipelines – to transport this new energy wealth (Sorgo [...], 2025; Bachion & Arantes, 2026).

1. The Maize Revolution: Production, Market Dynamics, and the Rise of the Second Crop

1.1. The Agronomic Context: The Creation of Surplus Supply

The genesis of the maize ethanol industry in Brazil does not lie in a public policy of subsidizing consumption, but rather in a market solution to a logistical and overproduction problem. The state of Mato Grosso, and subsequently its neighbors in the Central-West and Matopiba regions, developed a unique capacity to achieve two full commercial grain harvests in the same agricultural year. Soybeans, harvested between January and March, free up the soil for the immediate planting of maize (or sorghum), which develops by taking advantage of the residual soil moisture and the last rains of the tropical summer (União Nacional do Etanol de Milho, 2026b).

Historically, this "second-crop maize" faced a huge logistical bottleneck. Produced approximately 2,000 kilometers from the export ports (Santos/SP or Paranaguá/PR) and with deficient storage infrastructure, the maize from Mato Grosso suffered from being an extremely unattractive agricultural business. In practical terms, the price of maize in the interior of Mato Grosso was among the cheapest in the world, as freight costs eroded the producer's margin. It was in this scenario of abundant and depreciated raw materials that the opportunity for industrial arbitrage flourished: instead of transporting cheap grains by expensive means, the industry began to transform the grain locally into high value-added products (ethanol and protein), "exporting" density instead of volume (União Nacional do Etanol de Milho, 2026b).

1.2. Production Data and The Scale Jump

The numbers describing the trajectory of maize ethanol are superlative and indicate a structural disruption in the market. In just ten years, production went from being a statistical trace to becoming the main driver of growth in the supply of biofuels in the country.

In the 2024/2025 harvest, maize ethanol production registered robust growth of 30.7% compared to the previous cycle, reaching a consolidated volume of 8.19 billion liters. This volume is not just a supplement; it was crucial for ensuring national supply security. During this same period, the sugarcane harvest in the Center-South region faced climatic challenges that resulted in a 10.7% drop in agricultural productivity (tons of sugarcane per hectare) and a nearly 5% decrease in total milling. Maize ethanol, therefore, acted as a buffer that prevented a supply and price shock in the fuel market, ensuring that the total volume of ethanol (sugarcane + maize) reached a record 34.96 billion liters (Produção […], 2025).

The representativeness of maize grains in the ethanol matrix is growing and irreversible. In the 2024/2025 harvest, with total production of maize grains of approximately 127 million tons, maize represented about 20% of the country's total ethanol production. Projections from the National Union of Corn Ethanol (UNEM) and specialized consultancies indicate that, by the end of the 2025 calendar year and the beginning of the 2025/2026 harvest, production should break the 10-billion-liter barrier. With this volume, grain ethanol will surpass the 25% mark of participation in the national market (Produção […], 2025). This expansion is driven by the start-up of new units and the expansion of the capacity of existing plants, especially in the states of Mato Grosso and Goiás.

The evolution and projections of production, highlighting the aggressive growth curve of this sector compared to the mature stability of the traditional sugar-energy sector, are summarized in Table 1.

The local economic impact of this transformation is measurable. Mato Grosso, the epicenter of this movement, projects to produce 6.7 to 7 billion liters of maize bioethanol in the 2025/2026 harvest. This volume consolidates the state not only as the country's "breadbasket," but also as its renewable "battery." The industrialization of maize has allowed the state to maintain GDP growth rates well above the national average, shielding the regional economy from price fluctuations of the raw commodity (Mato Grosso […], 2026).

2. Biorefineries and Bioenergy from Starchy Plants: The Case of Maize and Sorghum

The bioenergetics of starchy plants and grains (rich in starch – plant energy bank) is based on the conversion of light energy (radiant, electromagnetic) into chemical energy (via photosynthesis), resulting in the synthesis of glucose, which is polymerized into starch – a polymer of amylose and amylopectin. In higher plants, this carbohydrate, insoluble in cold water, is densely stored in roots, tubers, and

Table 1. Growth of the sugarcane energy sector and production projections between the Flex and Full segments (sugarcane and maize).

Indicator	2023/24 Crop	2024/25 Harvest (Completed)	Crop season 2025/26 (Projection)	Growth
Maize Ethanol Production (Billions of Liters)	~6.26	8.19	~10.00	+22% to +30%
Maize's share in the total mix (sugarcane + maize)	~18%	23.43%	>25%	Continuous Expansion
Estimated Maize Milling (Millions of tons)	~14.0	~18.5	~22.5	Demand Growing
Estimated Sector Revenue (Industrialization)	-	-	Growth > 20%	Added Value

Source: Produção […] (2025), União Nacional do Etanol de Milho (2026b).

seeds as an energy reserve, and is subsequently hydrolyzed (broken down by the action of water and enzymes) to support metabolism, growth, germination, and plant reproduction.

The bioenergetics of the plant (photosynthetic efficiency, with approximately 90% of its dry matter derived from CO_2 fixation) and of the maize grain (energy density of starch, with glucose energy ($C_6H_{12}O_6$) produced for the entire plant and the surplus stored in the grain as starch – energy storage in the endosperm of the grain, with a metabolizable value of approximately 3,381 kcal/kg) (Rostagno, 2017), translates the pillars of a complex, efficient, and productive energy system, with anabolic actions and processes – capture and storage, via photosynthesis, synthesis of starch stored in chloroplasts and reserve organs (cereal seeds, also in cassava roots and potato tubers), in starch granules; catabolic actions and processes – energy mobilization, by enzymatic degradation (amylases break down starch into glucose) and cellular respiration (with glucose released in the mitochondria to produce adenosine triphosphate, ATP – energy that promotes growth and reproduction).

The bioenergetics of maize (*Zea mays*) stands out for the energy dynamics in the plant, with high efficiency in converting sunlight into biomass, as a C_4 plant (metabolism that uses the photosynthetic pathway as a carbon concentrating mechanism, reducing photorespiration), which allows for superior carbon fixation and massive energy accumulation in the form of starch (60-70% in the grain) and oils (15-20 kg/t maize) (García-Lara et al., 2019; Matos et al., 2023; Machado et al., 2026). In addition to human and animal food, starchy grains are fundamental to the agroenergy sector, for example, as raw materials for biofuels and industrial processing. As an agro-industrial raw material, both environmental stress (droughts or extreme temperatures that reduce starch biosynthesis and impair the plant's energy reserves and grain quality) and storage under inadequate humidity and heat conditions (which increase the respiration rate of stored grains, consuming starch prematurely and generating losses of dry matter and energy) can be relevant factors.

In starchy raw materials, the industrial production of biofuels (bioethanol) and the efficiency in generating co-products (DDG – 300 kg/t maize, rich in fiber, protein and oils for high-protein animal feed, such as DDGS and WDR/WDS – “Wet Distiller’s Grains” / “Wet Distiller’s Grains with Solids”), follow sequential steps in the production flow, allowing the biofactory to operate throughout the year, including physical processes (grinding and preparation); starch hydrolysis (liquefaction and saccharification) in bioreactors with the addition of water and specific amylase enzymes under controlled temperature; fermentation of the must (solution rich in glucose) with yeasts (*Saccharomyces cerevisiae*) that convert the sugar into ethanol and CO_2; distillation and dehydration (heat the fermented mixture to separate ethanol from water) with high efficiency and separation of co-products , yielding 390-430 liters of ethanol per ton of processed maize. (Note: Sugarcane produces approximately 70 to 90 liters of ethanol per ton of cane, with sucrose $C_{12}H_{22}O_{11}$ as the main carbohydrate).

The modern concept of biorefineries includes raw materials characterized as a central element of energy transfer systems, conversion processes, and uses. Energy efficiency and energy density are the components that link the agronomic and industrial routes to the structured business of biomass energy.

Technological roadmaps of renewable raw materials for energy purposes provide opportunities for the production and use of biomass energy via technological routes – biological, biochemical, thermochemical (gasification/pyrolysis/catalytic reforming) – with mastery of knowledge, adaptation of technical, productive and marketing strategies, and contribute to the modeling and decision-making in bioenergy systems of plants, organs or products of interest in the bioenergy and chemical industry – products, processes and co-products for ethanol, biodiesel, bioelectricity, biomolecules and biomaterials.

Plant biomass for energy purposes relies on starchy products, such as maize and sorghum, as organic raw materials for energy production. The maize kernel is a caryopsis-type fruit and a concentrated source of energy, with a chemical composition rich in starch, protein, oil, and fiber. The energy consumed to produce the grains varies depending on the variety, growing conditions, and processing, but maize is a net producer of energy, with high gross energy density. Energy density (gross energy consumed) is a measure of the energy contained per unit mass, and the maize kernel has an average value of 18.6 MJ/kg, or 4,450 kcal/kg (Liska et al., 2009; Zhao al., 2018; Machado et al., 2026).

The bioenergetics of maize kernels consider the energy density consumed and produced per gram. It is important to note that the energy density produced (metabolizable energy) is always less than that consumed (gross energy), as there are losses during digestion and metabolism of food in different animals. The gross energy value of maize kernels is a theoretical estimate of all the energy it contains. A reference value for dry maize is approximately 419 kcal per 100 grams. Considering 1 kcal = 4.184 kJ, the gross energy density of maize is about 17.54 kJ/g.

Most of the energy from maize comes from starch – a carbohydrate that represents between 60% and 70% of the grain’s composition. During digestion, starch is broken down into simple sugars (glucose monomers), which are absorbed and used for various metabolic functions. Maize also contains lipids (mainly in the germ) and proteins, which contribute to energy production, albeit to a lesser extent. Factors affecting the energy value of maize for animals include its density, which is related to its starch and oil content. A denser grain usually has more starch and less fiber, resulting in higher metabolizable energy. Additionally, an important factor is starch digestibility, which varies according to the grain's maturity and processing. Research indicates that maize production results in a positive net energy gain; however, specific values depend on agricultural practices and processing methods. These relationships demonstrate that maize production has a positive energy balance, with most of the final energy content derived from solar energy captured during photosynthesis. However, a significant portion of energy inputs comes from non-renewable sources, mainly in the production of fertilizers, fuel for machinery, and irrigation. Currently, it is estimated that for every unit of fossil energy used in the production of maize ethanol, approximately 1.5 to 2.5 units of renewable energy are obtained.

3. The New Logic of Biorefineries: Infrastructure and Industrial Model

A deep understanding of the phenomenon requires a terminological and conceptual distinction: the modern maize ethanol plant is not a "distillery," it is a biorefinery. While the traditional sugarcane mill is designed to grind stalks, extract sugar, and ferment the sugarcane juice or the residue from sugar production (molasses), the maize biorefinery is designed to fractionate the grain into its basic chemical constituents—starch, protein, fiber, and oil—and valorize each of them independently (União Nacional do Etanol de Milho, 2026a).

3.1. The Industrial Park: Full and Flex Plants

Brazil has developed a unique hybrid industrial plant model for ethanol production. While the United States operates plants dedicated exclusively to maize (using fossil natural gas as an energy source), Brazil operates two distinct models, both using renewable biomass (eucalyptus, bagasse, wood chips) for energy generation (steam and electricity), giving Brazilian ethanol a significantly smaller carbon footprint (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2022).

Currently, the Brazilian industrial park comprises approximately 20 to 25 significant units, divided into two categories:

"Full" Plants: These are plants designed exclusively to process grains (maize and sorghum). They operate 365 days a year, stopping only a few days for scheduled maintenance. They are not dependent on sugarcane harvest and have high-pressure boilers specifically for burning forest biomass or waste, which generate steam and electricity, supplying the needs of the industrial operation and generating a surplus of electricity that is sold to the distribution network. There are about 10 units of this type in full operation, the largest belonging to Inpasa and FS Bioenergia (Produção […], 2025).

Flex" plants: These are traditional sugarcane plants that have undergone retrofitting to incorporate a maize processing unit. This allows the plant to process sugarcane during the harvest season (April to November) and maize during the off-season (December to March), or process both simultaneously to maximize tank utilization and energy generation. There are approximately 10 to 15 plants operating under this model, optimizing industrial fixed assets that were previously idle during the sugarcane off-season (Produção […], 2025).

3.2. The Expansion Map: Investments and New Projects

The sector is experiencing an extremely aggressive capital investment (CAPEX – "Capital Expenditure") cycle. The National Union of Corn Ethanol (UNEM) has mapped approximately R$ 40 billion in investments earmarked for the construction of new plants and the expansion of existing ones in the coming years. The pipeline of projects includes 16 new plants already authorized and another 16 in the planning and environmental licensing phase (Produção […], 2025).

The geography of these new industrial plants reveals a trend towards inland expansion and decentralization:

Mato Grosso (The Consolidated Hub): Continues to receive most expansion investments. Inpasa, the largest producer in Latin America, has gigantic plants in Sinop and Nova Mutum, with production capacities exceeding billions of liters annually. FS Bioenergia, a pioneer in the "full" model, operates in Lucas do Rio Verde, Sorriso, and Primavera do Leste, and continues to expand its capacity (FS Bioenergia, 2026).

Mato Grosso do Sul (The New Frontier): The state is replicating the successful model of its neighbor. Inpasa inaugurated operations in Dourados and announced a new plant in Sidrolândia. The logic is the same: to take advantage of the surplus of local second-crop maize and the proximity to consumer markets of Paraná and São Paulo (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2025a).

Matopiba (The Northeast Expansion): The most recent strategic move is the expansion of businesses to the North and Northeast. Inpasa announced investments in Balsas (Maranhão) and Luís Eduardo Magalhães (Bahia). 3Tentos, a traditional agribusiness company from Rio Grande do Sul, is investing R$ 1.2 billion in Porto Alegre do Norte (MT), on the border of Pará/Tocantins. This geographic dispersion is crucial to reduce logistical dependence and serve regional markets of fuels and animal feed that currently depend on imports from other states (Produção […], 2025).

3.3. Biorefinery Engineering

The efficiency of these new industrial plants is remarkable. Unlike sugarcane, where the perishable raw material (with 70% water) travels a maximum of 50km to be processed at the mill, maize (a dry product with 13% moisture) can travel 500km and be stored in silos for months without loss of quality. This allows for precise industrial planning.

The industrial process converts 1 ton of maize into approximately three-thirds of its economic value: bioethanol, DDG/WDG co-products, and maize oil (Table 2).

3.4. Biorefineries for Maize and Sorghum Ethanol in Brazil: Private and Public Efforts

Table 2. Conversion of 1 ton of maize into commercial products and co-products*.

Product/Co-product	Quantity and Unit
Ethanol (liquid energy)	~400 to 420 liters
DDG/WDG (protein and fiber)	~300 kg
Maize oil (high-value lipids)	~18 kg
CO2 (biogenic carbon dioxide, capable of being captured)	~300 kg

*Data prepared by authors considering different sources.
Source: Bothast and Schlicher (2005), União Nacional do Etanol de Milho (2025), Renewable Fuels Association (2023).

Towards a Clean and Sustainable Energy Matrix

The use of ethanol from starchy raw materials, especially grain cereals such as maize and sorghum, in the production of biofuel and DDG/DDGS and WDG co-products is growing in regions of Brazil, seeking to enhance local production capacity of grains, promote added value to production, generate more jobs and income, and promote regional integration and development, with raw materials, products, and co-products from the biorefinery.

The various co-products generated from grain ethanol production, such as oil, maize syrup, and DDG/DDGS, have high added value and tend to play a relevant role in regional economic development. Especially relevant is the role of DDG/DDGS use in the intensification of livestock farming in Brazil, which will contribute to adding market value to animal proteins and freeing up areas that could be used for agricultural production but are currently used for animal feed. According to the National Maize Ethanol Union (União Nacional do Etanol de Milho, 2025), for each ton of maize used in ethanol production, approximately 420 liters of ethanol, 212 kg of DDGS, and 19 kg of maize oil are generated. Data from the Mato Grosso Institute of Agricultural Economics (IMEA) indicate that Brazilian DDG/DDGS production increased from 2.7 million tons in the 2023/24 harvest to 4.1 million tons in 2024/25, with a forecast of reaching 4.8 million tons in the 2025/26 harvest.

Over the last 10-15 years, ethanol production from maize and sorghum has been expanding, especially in the Midwest and Southeast regions of Brazil. There are also clear signs of expansion in other regions, seeking competitive advantages such as: current and potential availability of grains; increased use of biomass energy for commercial purposes; supply of co-products for the animal protein chain; favorable edaphoclimatic conditions for grain cultivation; increased functionality of sugarcane mills modernized to operate as "flex" biorefineries, in addition to the installation of biorefineries dedicated to starches; mitigation of dependence on biofuel imports from other producing regions; and increased predictability and security for grain producers, anchored in demand and negotiation in the futures market.

UNEM signals a growing sector with a

rapidly developing industry, listing 24 units in operation, 16 authorized, and 16 announced, with strategic partners and objective support from important agro-industrial and sustainable economic development agencies.

3.5. History and trends of maize and sorghum crops in Brazil - the "Brazilian sorghum belt"

Brazil has technologically advanced tropical agriculture with a history of increasing yields; however, it is an "open-air" system with both great opportunities and risks

Productivity and efficiency, "production stability" in the face of "environmental instabilities", complex intensified systems (rotation, succession, intercropping, integrated crop-livestock-forestry systems, integrated crop-livestock-forestry systems) for grain production and their association with animal protein chains, diversification of supply and value addition to products through agro-industrial processing, entrepreneurship and technologies are all conditions and requirements, in constant evolution, for the modernization of Brazilian agriculture and agro-industry.

The history and evolution of series of production, productivity, and cultivated area of maize (total, 1st, 2nd, and 3rd harvests) and grain sorghum in Brazil demonstrate the alignment of these variables with innovation assets and the relevance of free knowledge – intangible – for the impact on crops and Brazilian agricultural production in different territorial regions, planting seasons, and use of physical inputs (including soil amendments and fertilizers, cultivars, and pesticides/defensives).

The analysis of the historical series of planted area, production and productivity of grains in Brazil, by region (5) and federative unit (27), based on 10 summer species and 5 winter species, over 50 harvests – 1976/1977 to 2025/2026, shows significant evolution.

For total maize production (1st, 2nd and 3rd harvests), over the 50-harvest period, there was an increase of 1.93 times in planted area, 3.7 times in productivity and 7.2 times in production (Table 3).

In 1976/77, the total maize harvest (1st, 2nd and 3rd crops) in Brazil had a planted area of 11,797.3 thousand ha, a grain production of 19,256 thousand tons, and a grain productivity of 1,632 kg/ha. For 2025/26, an estimated planted area of 22,727.9 thousand ha, a grain production of 138,879.0 thousand tons, and a grain productivity of 6,111 kg/ha are projected, according to a historical series of 50 crops (Conab, 2026a) (Table 3 and Table 4).

Evaluating the case of grain sorghum, over a period of 50 harvests, a 10-fold increase in planted area, a 1.5-fold increase in productivity, and a 15-fold increase in production were observed (Table 5).

The growth observed over these five decades demonstrates widespread use of grain sorghum across all Brazilian regions, with an expansion of cultivated area and increases in production volume and productivity. However, a concentration of grain sorghum cultivation and production is observed in the Central-Southeast region, especially in the states of GO, MG, DF, and BA, constituting what is known as the "Brazilian sorghum belt"(Figure 1) (Rios et al., 2026).

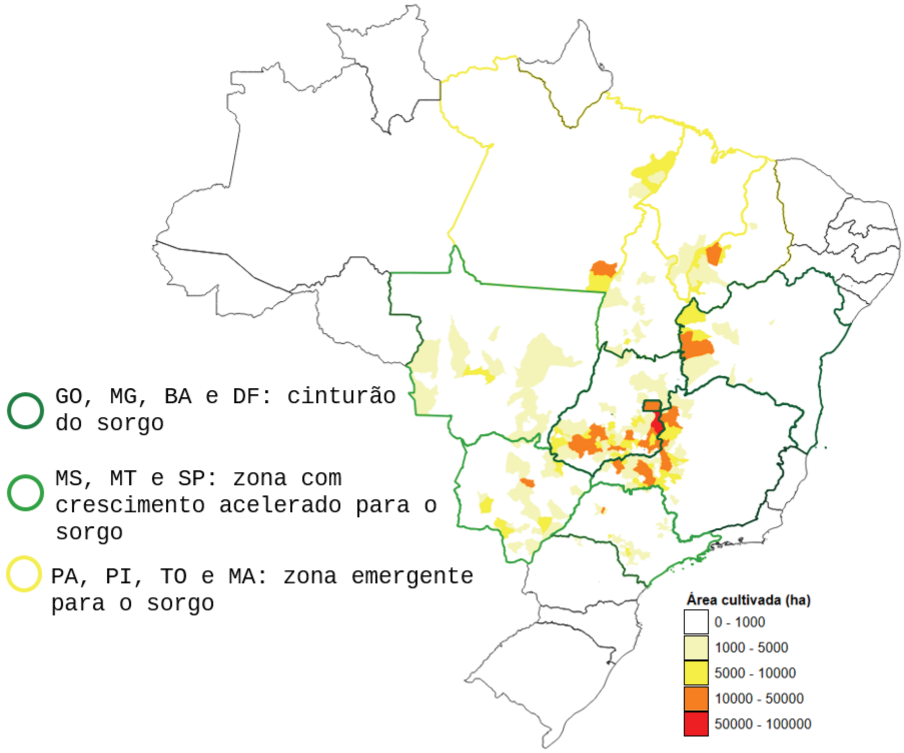

Figure 1. Identification of producing regions and delimitation of representative zones of different sorghum realities in Brazil. *Data on average municipal cultivated areas for 2022, 2023 and 2024. Source: IBGE (2026).

4. Sorghum as a Strategy for Resilience and Complementarity

Second-crop ("safrinha") cultivation is, by definition, a risky agricultural activity. Planting occurs at the end of the rainy season, and the crops need to develop with the moisture stored in the soil, racing against the clock before the winter drought or early frosts arrive.

Maize is sensitive to this stress. Grain sorghum, on the other hand, possesses physiological characteristics of resistance to drought and heat - a deep root system and the ability to remain dormant during dry periods - which give it the nickname "vegetable camel". In El Niño years, when rainfall is delayed and the ideal maize planting window is reduced (closing in February), sorghum becomes the only viable option for farmers to plant in March and still obtain a harvest. Historically, grain sorghum had a reputation as the "poor cousin" in ethanol production, with lower industrial yields and tannins that hindered enzymatic hydrolysis and fermentation. However, recent genetic improvements and the development of specific enzymes have leveled the playing field.

Yield: Modern varieties of grain sorghum without tannins have industrial yields of 380 to 400 liters of ethanol per ton, very close to the 400 to 420 liters obtained with Maize. Given that the cost of sorghum production can be 20% to 30% lower (fewer seeds, less fungicide use), the industry's

Table 3. Partial historical series of **maize cultivation in Brazil** (harvests 1976/1977 to 2025/2026*)

Brazil. Total Maize Harvests (1st, 2nd and 3rd crops)			Planted Area (thousand ha)		Productivity (kg/ha)		Production (thousand tons)	
Harvest	**Nr.**	**Crop**	**Value**	**% (base 1976/77)**	**Value**	**% (base 1976/77)**	**Value**	**% (base 1976/77)**
1976/77	**1**	**Total**	**11,797.3**	**100.0**	**1,632.0**	**100.0**	**19,256.0**	**100.0**
		1a	11,797.3	100.0	1;632.0	100.0	10;255.7	100.0
		2a	...	...	...	...	...	...
		3a	...	...	...	...	...	...
1980/81	**5**	**Total**	**12,147.1**	**103.0**	**1,752.0**	**107.4**	**21,284.0**	**110.5**
		1a	11,904.1	100.9	1,777.0	108.9	21,156.8	109.9
		2a	243.0	2.1	523.0	32.0	127.0	0.7
		3a	...	...	...	...	...	...
2000/01	**25**	**Total**	**12,972.5**	**110.0**	**3,260.0**	**199.8**	**42,289.7**	**219.6**
		1a	10,546.1	89.4	3,398.0	208.2	35,833.0	186.1
		2a	2,426.4	20.6	2,661.0	163.1	6,456.7	33.5
		3a	...	...	...	...	...	...
2020/21	**45**	**Total**	**19,943.6**	**169.1**	**4,367.0**	**267.6**	**87,096.8**	**452.3**
		1a	4,348.4	36.9	5,686.0	348.4	24,726.5	128.4
		2a	14,999.6	127.1	4,050.0	248.2	60,741.6	315.4
		3a	595.6	5.0	2,734.0	167.5	1,628.5	8.5
2025/26	**50**	**Total**	**22,727.9**	**192.7**	**6,111.0**	**374.4**	**138,879.0**	**721.2**
		1a	4,043.1	34.3	6,408.0	392.6	25,907.0	134.5
		2a	18,092.7	153.4	6,105.0	374.1	110,461.0	573.6
		3a	592.1	5.0	4,241.0	259.9	2,510.9	13.0

*Estimate[23] as of December 2025

Crops 1 to 50: Total Maize (1st, 2nd and 3rd crops)
Area (thousand ha): increased 1.93 times; Productivity (kg/ha): increased 3.7 times; and Production (thousand t): increased 7.2 times.

Table 4. Historical Production Series (in thousand tons) of 50 Maize Crops in Brazil, from 1976/77 to 2025/26 (*). (Percentage of total annual production in the 1st, 2nd and 3rd crops)

Maize		**Relative Production (%) of Maize Grains, by crop season**		
Year (Series)	**Harvest**	**1st Crop**	**2nd Crop**	**3rd Crop**
1	1976/77	100.0	...	...
5	1980/81	99.4	0.6	...
15	1990/91	95.6	4.4	...
20	1995/96	89.2	10.8	...
25	2000/01	84.7	15.3	...
30	2005/06	74.8	25.2	...
...	...	...	...	...
35	2010/11	60.9	39.1	...
36	2011/12	46.4	53.6	...
37	2012/13	42.4	57.6	...
38	2013/14	39.5	60.5	...
39	2014/15	35.5	64.5	...
40	2015/16	38.7	61.3	...
41	2016/17	31.1	68.9	...
42	2017/18	33.3	66.8	...
43	2018/19	25.6	73.1	1.3
44	2019/20	25.0	73.2	1.8
45	2020/21	28.4	69.7	1.9
46	2021/22	22.1	75.9	1.4
47	2022/23	20.8	77.6	1.6
48	2023/24	19.9	77.9	2.2
49	2024/25	17.7	80.3	2.0
50	2025/26(*)	18.7	79.5	1.8

*Historical series[1] – Grains. (*) Production estimate.

Table 5. Partial historical series of grain sorghum cultivation in Brazil (crops 1976/1977 to 2025/2026*).

Harvest	Crop No.	Planted Area (thousand ha)		Productivity (kg/ha)		Production (thousand tons)	
		Value	% in relation to 1976/77	Value	% in relation to 1976/77	Value	% in relation to 1976/77
1976/77	1	177.6	100.0	2,450	100, 0	435.1	100.0
1980/81	5	97.7	55.0	2.335	95.3	228.1	52.4
2000/01	25	502.0	282.7	1,784	72.8	895.7	205.9
2020/21	45	864.6	496.9	2,410	98.4	2,084.2	479.0
2025/26*	50	1,796.0	1,011.3	3,684	150.4	6,616.0	1,520.6

Source: Conab (2026b).
(*) Production estimate.

profit margin is highly competitive (Reis, 2025). **Vertical Integration:** Large biorefineries have realized they cannot rely solely on maize. Inpasa, in strategic partnership with Embrapa Maize and Sorghum, has launched massive incentive programs for sorghum cultivation. The industry provides the technology and guarantees the purchase of the product (via futures contracts), encouraging producers to cultivate areas that would otherwise remain fallow. The goal is to create a "sorghum belt" around the plants to guarantee a supply of starch even in years of maize crop failure (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2025a).

Field Data: The area planted with sorghum has already reached 1.59 million hectares, with production reaching almost 6 million tons (Conab, 2026b). The trend is for vertical growth as more mills adapt their receiving and grinding facilities to process this cereal (Sorgo […], 2025).

5. The Protein and Energy Complex: Far Beyond the Ethanol

The "new biorefinery logic" cited as a central theme refers to revenue diversification. A modern plant cannot survive solely on ethanol sales, especially during periods of low petroleum prices. Financial robustness comes from revenue obtained from co-products: protein (DDG), oil, and electricity.

5.1. DDG and WDG: The Intensive Livestock Farming Revolution

The most voluminous co-products of maize ethanol production are "Distiller's Dried Grains" (DDG) or their wet version (WDG). The enzymatic hydrolysis and fermentation process consumes only starch from the grain; proteins, fiber, fats, and minerals remain concentrated in the solid residue, thereby tripling its nutritional density compared to the original maize (União Nacional do Etanol de Milho, 2026a).

Synergy with Livestock Farming: Brazil has the world's largest commercial cattle herd. The abundant supply of DDG/WDG in the Midwest has allowed for an explosion in cattle feedlots. WDG, being moist and perishable, is sold at competitive prices to feedlots within a 100-150 km radius of the processing plant, creating a local ecosystem of intensive fattening. The animal gains weight faster, improves meat quality, frees up pasture earlier, and frees up grazing areas for other crops (Produção […], 2025).

Export Market: DDG is a global commodity. FS Bioenergia, for example, produces more than 2.2 million tons of animal nutrition products annually, exporting to demanding markets such as Vietnam, Turkey, and New Zealand, in addition to supplying the domestic swine and poultry industries (FS Bioenergia, 2026).

5.2. Maize Oil

Maize oil, extracted by centrifugation before or after the fermentation stage, has become an important contributor to industrial profit margins.

Added Value: Efficient oil extraction (15 to 18 kg per ton of processed maize) generates additional revenue that, in many cases, covers the plant's operating costs. Without oil extraction, the lipid would be "lost" within the DDG, being sold at the price of bran (Sinop, 2025).

Uses: In addition to culinary use, maize oil from the ethanol plant is a premium raw material to produce biodiesel and, in the future, green diesel (HVO) and sustainable aviation fuel (SAF), due to its low acidity index and traceable sustainability. Maize oil exports hit a record in April 2025, reaching US$55.2 million, with Goiás and Mato Grosso leading shipments (Sinop, 2025).

5.3. Bioelectricity and Biomethane

Biorefineries are self-sufficient in energy. They burn biomass (planted eucalyptus wood chips) to generate steam and electricity. The steam is used in industrial processes, and the surplus electricity is sold to the grid, providing stable, predictable revenue. Furthermore, process waste and vinasse are being digested to produce biomethane, which replaces diesel in the fleet of trucks that transport the maize itself, closing the carbon loop of logistics (União Nacional do Etanol de Milho, 2026a).

6. Sustainability: Demystifying Impacts and Land Use

6.1. The "Second Crop" Mechanism and Land Use

Brazilian ethanol production from maize/sorghum occurs primarily from the "safrinha" (second crop). This means that these grains do not expand into new areas of native vegetation; they occupy areas that have already been cleared and are cultivated with soybeans in the summer.

Intensification of Land Use: By planting maize/sorghum after soybeans, the farmer keeps the soil covered (protecting against erosion), recycles nutrients, and generates extra income in the same physical area. There is no "Opening of New Areas" for ethanol production; there is optimization of the use (intensification) of existing areas (Bachion & Arantes, 2026).

6.2. ILUC (Indirect Land Use Change) and the Land-Saving Effect

International critics often cite ILUC

(“Indirect Land Use Change”) — the theory that using maize for ethanol would displace other crops or livestock farming, which would otherwise expand into forest areas. In Brazil, strictly speaking, the opposite occurs, a positive phenomenon of productive intensification.

The Virtuous Cycle: The biorefinery generates DDG as a co-product, which enables cattle feedlot systems. The adoption of feedlots reduces dependence on extensive pasture, freeing up areas previously occupied by degraded pastures. These areas can then be incorporated into agricultural production of crops such as soybeans and maize, without the need to open new areas or deforest to expand production.

Scientific Evidence: Studies using general equilibrium models (GTAP) demonstrate that the expansion of ethanol in Brazil, when accompanied by the supply of co-products for animal feed, reduces pressure on forests by inducing the modernization of livestock farming. Maize ethanol, therefore, acts as a tool for indirect preservation (Gazzoni, 2024).

6.3. RenovaBio and Energy-Environmental Efficiency (NEEA)

Sustainability is measured and audited by the federal RenovaBio program – a biofuels public policy established by Law 13.576/2017. The Program establishes annual decarbonization targets for the fuel sector, to encourage production and expand the participation of ethanol and biodiesel in the country’s transportation energy matrix (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2025b).

Energy and Environmental Efficiency Rating (EEER): Maize ethanol plants have achieved strong EEERs. While American maize ethanol (made with fossil fuels) has a high carbon footprint, Brazilian maize ethanol (made with eucalyptus biomass energy and delivering electricity through cogeneration) achieves competitive emission reduction ratings, frequently exceeding 60-70 gCO2eq/MJ reductions compared to the American version (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2022).

BECCS (Bioenergy with Carbon Capture and Storage): The final frontier of sustainability is being explored by FS Bioenergia in Lucas do Rio Verde. The fermentation of maize must releases carbon dioxide (CO_2). The company has developed a project to capture this CO_2 and inject it into deep geological formations (basalt). When implemented, this will make Brazilian maize ethanol the world’s first fuel with a negative carbon footprint on an industrial scale; in other words, a car using this ethanol will, in practice, be “cleaning” the atmosphere as it drives (FS Bioenergia, 2026).

6.4 Localized water risks

Bioenergy production from biomass requires different dynamics of water and energy efficiency. While sugarcane is highly self-sufficient and productive per area, corn and other grain cereals (e.g., maize, sorghum, wheat) depend on more intensive industrial processes, offset by the flexibility of year-round production. Essentially, it is an agro-industrial strategy based on energy density and efficiency. Agricultural productivity and energy conversion vary significantly among biomasses, and the energy conversion rate per hectare, energy balance, carbon footprint, and industrial water consumption in processing are associated with water balance and water risks. Exposure to water risks is the main distinction between crops – saccharides (sugarcane) and starchy grain crops (corn, sorghum, wheat), and this is because industrial consumption varies depending on the type of conversion (direct fermentation of sugarcane juice versus liquefaction/hydrolysis of starch). In industrial use, water enters the mills with the sugarcane (about 70% of the weight of the stalks) and with the intake for industrial uses. The water captured is used in various processes, with different levels of reuse; a portion is returned to watercourses after the necessary treatments, and another part is destined, along with vinasse, for fertigation. The difference between the water captured and the water discharged is the water consumed internally (processes) (Gerbens-Leenses et al., 2009).

When evaluating alternative feedstocks, the selection of biomass radically dictates the localized water risks and overall sustainability of the biorefinery. On a global energy-equivalent basis, sugarcane shows clear superiority over alternative grain-based feedstocks; its water footprint for bioethanol production sits at approximately 110m^3/GJ, sharply outperforming sorghum, which ranks as the most water-inefficient pathway at over 400m^3/GJ due to lower energy conversion rates per hectare (Gerbens-Leenes et al., 2009). While US corn-derived ethanol exhibits a smaller total life-cycle volumetric water consumption per liter 541L/L compared to Brazilian sugarcane 1,115 L/L, sugarcane biorefineries yield a vastly superior net energy balance 17.7MJ/L vs. 11.2 MJ/L for corn) and a lower carbon footprint (Mekonnen et al., 2028). Furthermore, the long-term industrial landscape favors sugarcane processing in tropical zones. Driven by modern closed-loop upgrades - including dry cane washing, rigorous condensate recovery, and wastewater recycling - the actual industrial water consumption of sugarcane processing has declined by roughly 95% over recent decades to a highly efficient 0.56m^3 per metric ton of biomass (Barroquela et al., 2023). This steep drop in blue water demand minimizes industrial competition with local water basins, a mitigation benefit that grain starch facilities processing maize or sorghum struggle to match without sacrificing their net energy advantages.

7. Socioeconomics and Logistics: Development and its Bottlenecks

7.1. Impact on HDI and Municipal GDP

The installation of biorefineries has transformed inland cities into islands of prosperity. Municipalities such as Sinop, Lucas do Rio Verde, and Sorriso boast Human Development Index (HDI) scores higher than many state capitals. However, regional development literature cautions that rapid, resource-driven economic expansion can inadvertently widen socioeconomic gaps and strain local infrastructure if not accompanied by robust municipal planning. Studies from institutional frameworks like the OECD and urban planning journals indicate that sudden population influxes in regional hubs often trigger acute deficits in public services, specifically housing inflation, healthcare saturation, and heightened intra-municipal inequality. Therefore, translating macroeconomic indicators into comprehensive, long-term social well-being requires proactive public-private strategies that mitigate these collateral pressures and ensure structural stability across all segments of the population (Kirshner et al., 2022; Uhr et al., 2024).

Job Quality: Unlike agriculture, which employs seasonally, the industry employs more highly skilled workers (engineers, chemists, biologists, among others) and technicians (for process operation, maintenance, instrumentation, quality control, among other functions) throughout the year, with high salaries. The construction of a single ethanol plant generates more than 8,000 direct and indirect jobs, and its operation maintains thousands of permanent jobs (Nardy & Gurgel, 2013).

Revenue: The added value generated by industrial processing multiplies the tax base (ICMS, ISS) of municipalities, allowing for public investments in quality health and education. In Sapezal, for example, agribusiness accounts for more than 53% of the local GDP (União Nacional do Etanol de Milho, 2026b).

7.2. The Logistics Challenge: Ferrogrão and Ethanol Pipeline

Production growth is usually faster than the development of distribution infrastructure. Ethanol produced in Mato Grosso needs to reach car tanks in São Paulo, in other states, or the ports for export. Currently, this is done mainly by trucks, burning diesel and increasing the cost of the product.

8. Knowledge Framework for Biorefineries of Ethanol and Co-products of Maize and Sorghum

Brazil can have three grain harvests annually. Tropical climate, adapted soils, and advances in agricultural technology, entrepreneurship, and structured and integrated arrangements (technical-scientific, institutional, and productive) explain the country's productive capacity, proven by the expansion and productivity of the business in the last five decades. The Brazilian strategy of promoting the soybean/maize combination – two important agricultural commodities – increases the availability of maize as a second crop, as well as offering opportunities for expanding first-crop maize cultivation and other grain species in regions with suboptimal environmental conditions. This is the case with the expansion of grain sorghum in territorial zones characteristic of a "Brazilian sorghum belt," consisting of large areas in Goiás, Minas Gerais, Mato Grosso do Sul, and southwestern Bahia; followed by important pockets in Matopiba and Pará, and in Mato Grosso, São Paulo, and Paraná.

Agriculture, livestock farming, agro-industry, biorefineries, and agro-energy plants, within the framework of a modernizing bioeconomy, seek to integrate competitiveness and sustainability for a highly efficient agro-environmental agenda, with adequate counterparts and returns from economic activity and corporate reputation, in alliances and partnerships. Thus, investments, costs, and returns on investments permeate business models and market scale, based on strategic territorial intelligence, territoriality, energy, technological routes, logistics, and stages of production and conversion of raw materials into products and co-products in regions of Brazil.

The agro-industry reveals distinct business models and bioenergy logics for specific technological roadmaps, based on energy efficiency and energy density.

8.1. Plants for Producing Bioethanol and Co-products: Sugarcane/Maize/Sorghum (Full) and Sugarcane/Maize (Flex)

Considering a knowledge framework or competitive opportunity map for biomass energy, via starchy species, including input-output matrix for raw materials, processes, arrangements (technical-scientific, institutional and productive), products and co-products, it is possible to comparatively establish the investment expenses in fixed assets (CAPEX) and operational costs (OPEX, "Operational Expenditure") for maize (Full) and sugarcane bioethanol plants.

Key governance and decision indicators for investment in sugarcane and maize (Full) plants consider the availability and cost of raw materials, seasonality, energy balance and conversion efficiency, and additional revenue through the sale of electricity (bioelectricity) and decarbonization credits (CBios) for sugarcane, and the sale of co-products (DDGS and oil) from maize. The territoriality and logistics of production, outflow, and supply of biomass, for the geography of ethanol in Brazil, are changing due to the expansion of maize production and uses in bioenergy for biofuels (bioethanol) and the animal protein value chain, and these factors distinguish the central-south region – dominated by sugarcane and flex-fuel plants – from the central-west region – the heart of maize production. In this context, in maize-producing regions with a lack of or deficit of planted forestry (eucalyptus), the cost of steam production may make a maize plant unfeasible. However, expanding the production of biomass for energy producion, via sorghum-energy, e.g., BRS 700 series cultivars, which are tall and have high calorific value, is a viable alternative to be considered.

A critical analysis of the landscape of maize ethanol industries in Brazil demonstrates that they are complementary, and not direct competitors of sugarcane, offering at least three perspectives to be considered: (a) Energy security: maize solves the historical problem of ethanol shortages during the sugarcane off-season (between January and March); (b) Market risk: maize plants are more vulnerable to geopolitical crises that affect grain prices. If the price of maize rises and the price of petroleum falls, the margin can quickly become negative; and (c) Sustainability: Brazilian maize ethanol has a very low carbon footprint because it uses biomass from reforestation and second-crop maize, unlike the American model that uses natural gas (fossil fuel).

8.2. Plants for producing bioethanol and co-products: Economic elements for implementing the project in terms of business models, locations, and availability of energy

sources

The choice between a Full plant (dedicated exclusively to maize) and a Flex plant (attached to a sugarcane mill) is a strategic decision that depends primarily on geographic location and access to energy sources (biomass).

The "Flex" plant offers synergy and asset optimization, being installed alongside sugar and ethanol production units, utilizing existing infrastructure to reduce the initial investment. It presents economic advantages such as reduced CAPEX, utilizing existing mills, boilers, water treatment, and distillation columns, focusing on the inclusion of grain reception, milling, starch hydrolysis, and DDG drying; it allows for the dilution of fixed costs, operating 350 days a year, leveraging salaries and maintenance; and it offers "low-cost" energy through the use of sugarcane bagasse.

8.3. Plants for producing bioethanol and co-products: Economic feasibility and contribution margin in the input-output matrix

Economic feasibility and contribution margin (maize price versus ethanol price + DDG co-product) can be simulated using the Crush Margin concept, which measures the difference between the cost of raw materials and the revenue generated by the final products. Alternatively, a simulation can be based on average market values (reference year, location, market availability), considering the processing of 1 ton of maize, obtaining three revenue sources: ethanol, DDG/DDGS, and maize oil. Thus, the composition of revenue (sales of final products), costs (inputs), and the result (contribution margin) allows for a critical analysis of the sensitivity to commodity price fluctuations.

Currently, a simulation of the contribution margin (input-product and co-product price) for processing 1 ton of maize allows us to establish the composition of revenue and costs, considering the products ethanol (420 liters), DDG/DDGS (300 kg) and maize oil (18 kg), resulting in approximately a 20% gross profit margin. Sensitivity analysis indicates that economic feasibility is highly influenced by commodity price fluctuations. The commercialization of co-products (DDG and oil), as well as the costs of raw materials (maize) and energy (biomass), inform comparative analyses of "Full" (maize) and "Flex" (sugarcane + maize) industrial plants, including cost reductions.

8.4. Plants for producing bioethanol and co-products: Industrial efficiency in maize ethanol production

Industrial efficiency in maize ethanol production is measured by the ability to convert the maximum amount of starch into fuel while minimizing thermal losses and maximizing byproduct recovery. In Brazil, this efficiency has reached global competitiveness levels, frequently surpassing the American model due to the use of renewable energy. Several indicators and technologies related to raw materials, production processes, products, and management, define this efficiency and underpin the competitive advantage in maize bioethanol production.

Indicators and technologies useful for industrial efficiency in maize bioethanol production basically address stoichiometric and fermentative yields; therefore, the focus on starch conversion into fermentable sugars and the effectiveness of selected yeasts is relevant. Thermal efficiency and energy integration are vital to maize since, unlike sugarcane, it requires cooking and greater control of heat use. Also, the type of milling (dry or wet) defines the efficiency profile, and automation and complete real-time industrial process control require monitoring sensors.

Specifically, the choice between dry and wet milling establishes distinct trade-offs regarding capital investment, process yield, and co-product valuation. Dry-grind milling represents the dominant commercial configuration, primarily due to its significantly lower initial fixed capital costs and a streamlined processing layout that grinds the entire kernel without a prior stepping phase (Assaf et al., 2024). Consequently, dry mills maximize ethanol production efficiency per bushel of grain, yielding approximately 15% more biofuel than conventional wet systems, but restricting the resulting co-products to lower-value animal feeds like Distillers Dried Grains with Solubles (DDGS) (Kurambhatti et al., 2019; Assaf et al., 2024). Conversely, wet milling requires a capital-intensive infrastructure to support biochemical fractionation and chemical steeping, resulting in higher initial expenditures and operational complexity (Kurambhatti et al., 2019). However, this infrastructure allows the plant to separate the grain into its core components before fermentation, generating premium, high-purity co-products such as high-protein corn gluten meal, corn germ meal, and food-grade oil, which command significantly higher market prices and diversify biorefinery revenues (Kurambhatti et al., 2019; Scully et al., 2024). Thus, while dry milling optimizes direct bioethanol volumetric outputs under restricted capital, wet milling drives superior economic elasticity by decoupling facility profitability from volatile fuel markets through high-value biochemical portfolios.

In the context of bioeconomy and sustainability, industrial efficiency is also measured by carbon intensity. The less fossil energy the plant uses and the more efficient its biomass combustion, the more CBios it generates, thereby creating direct financial revenue from the operation's environmental efficiency.

8.5. Plants for Producing Bioethanol and Co-products: Investments in the Construction of Typical Industrial Units for Maize Bioethanol

The CAPEX for constructing a maize bioethanol biorefinery (typical capacity in Brazil, processing ~500,000 to 1 million tons of grain/year) vary with the business model and scale (Table 6).

The OPEX of a maize and sorghum biorefinery is dominated by materials, but the business model stands out for generating revenue from co-products, which help offset fixed and variable costs. Maize and sorghum raw materials constitute the largest cost (Table 7).

The comparison between the return on investment (ROI) of a maize/sorghum plant and a sugarcane plant is a widely debated topic in the Brazilian sugar-energy sector. Although sugarcane has historically been the protagonist, the grain model offers specific financial advantages in asset utilization. Tables 8 to 12 highlight the main differences that impact the return on investment.

Table 6. Capital Expenditure (CAPEX) for the construction of a typical maize bioethanol plant in Brazil.

CAPEX Estimates (average construction cost of approximately R$ 3.50 per liter of installed capacity).	
Medium Plant ("Full")	Plants with a capacity of approximately 500,000 m³ of ethanol per year require around R$ 1.5 billion.
Mega-Power Plants	Large-scale projects (e.g., Inpasa in Rio Verde-GO or Balsas-MA) reach R$ 2.5 billion.
Smaller/Flexible Units	Smaller plants or adaptations in sugarcane mills ("Flex") can cost from R$ 250 million upwards.
Investment Composition (Amount of resources, in addition to industrial facilities)	
Grain Infrastructure	Silos and receiving systems for maize and sorghum represent approximately R$ 1,200 per ton of processing capacity.
Working capital	Essential for the advanced purchase of grains, potentially requiring an additional R$ 5 billion for the sector (~20% of industrial CAPEX).
Co-products	Equipment for producing DDGS (high-protein solubles from grains and starches) and maize oil is an integral part of the economic model.
Production Efficiency (Maize and Sorghum have similar yields, allowing the use of hybrid plants).	
Maize	~370 to 460 liters of ethanol per ton.
Grain Sorghum	~429.5 liters per ton.
Note: BNDES is one of the main financers of industrial maize bioethanol projects, via the Climate Fund.	

Source: Stamenković et al. (2020), Lorentz et al. (2025), Aghaei et al. (2022), Alqahtani (2024), Lorentz et al. (2025), Banco Nacional de Desenvolvimento Econômico e Social (2026b).

The metrics used to build this financial simulation reflect data models published in techno-economic literature on Brazilian biofuels. Key sources include the União Nacional do Etanol de Milho (2026c) regarding corn-to-DDGS yield conversions, and macro-assessments on corn ethanol infrastructure financing tracks from the BNDES (Banco Nacional de Desenvolvimento Econômico e Social, 2026a) and the Center for Advanced Studies on Applied Economics (Centro de Estudos Avançados em Economia Aplicada, 2026).

To analyze the actual feasibility, it is necessary to understand that a maize biorefinery is, in fact, a commodity arbitrage operation. Profit comes not only from industrial efficiency, but from managing the differential between the price of the grain (raw material, "input") and the

Table 7. The Operational Expenditure (OPEX) of a maize and sorghum biorefinery in Brazil.

Estimated cost per liter of maize ethanol production.	
Average Cost (Crop 24/25)	Estimated at R$1.88 per liter (a 10.5% reduction compared to the previous cycle).
Processing Margin	The direct cost of industrialization (excluding the grain) is around R$ 0.59 per liter, depending on the technology (dry or wet process).

Composition of OPEX (Main items)		
Raw material	(70% - 80% of OPEX): This is the most sensitive component.	
	Maize	Yield of approximately 450 liters/ton
	Sorghum	Yield of approximately 430 liters/ton
Energy and Utilities	Unlike sugarcane mills, maize/sorghum plants rely on external biomass (eucalyptus or wood chips) to power their steam boilers, unless they are integrated "Flex" plants.	
Chemical Inputs	Enzymes (alpha-amylase and glucoamylase), yeasts, antibiotics, and pH adjusting products.	
Maintenance and Operation	Preventive maintenance of equipment and facilities, cleaning of heat exchangers, and technical payroll.	

Reduced Revenue (The Differentiating Factor of Byproducts)	
The calculation of actual OPEX is often done using the "net cost," subtracting the sales value of co-products:	
DDGS	Each ton of maize yields approximately 230kg to 300kg of bran with a high protein content for animal feed.
Maize oil	Approximately 18 kg per ton of processed maize, used for biodiesel production or animal feed.

OPEX Comparison (Maize vs. Sorghum)

Culture	Yield (L/t)	Grain Production Cost (Base)	Technical Observation
Maize	~450	Approximately R$ 3,138.23/ha (Average) R$ 58.12/sack (Average MS) (Aprosoja, 2026).	Market standard, high liquidity.
Sorghum	~430	Approximately R$ 1,880.00/ha (Average)	Lower planting costs; excellent for dry-season crops.

Table 8. Comparison of the return on investment (ROI) of maize starch bioethanol plants versus sugarcane plants.

Asset Utilization Rate (The Determining Factor): the point at which maize and sorghum outperform sugarcane in the ROI calculation.	
Sugarcane	The plant operates an average of 200 to 240 days a year due to the off-season and rain that prevents harvesting. The capital investment remains "idle" for 4 months.
Maize/Sorghum	The plants operate 350 days a year. Because the grain can be stored, the industry spreads its fixed costs over a much larger annual production.
Impact on ROI	A maize plant produces almost 50% more fuel per year with the same industrial plant size as a sugarcane plant.

Comparison of capital expenditure (CAPEX) and ROI		
Indicator	**Sugarcane Mill (Traditional)**	**Maize Biorefinery (“Full”)**
Cash Cycle	Long (planting takes 12-18 months)	Short term (grain purchase at the market)
Industrial Availability	Seasonal (~7 months)	Continuous (12 months)
Estimated *Payback*	7 to 10 years	4 to 6 years
***EBITDA* Margin**	35% - 45% (volatile with sugar)	20% - 30% (more stable with DDGS)

The Role of Byproducts (Hedge of Risk): The ROI of the maize/sorghum plant is more resilient to fuel price crises.		
Indicator	**Sugarcane Mill**	**Maize Mill**
Financial Protection	In sugarcane mills, if the price of ethanol falls, the return becomes almost exclusively dependent on sugar.	In maize processing plants, DDGS (distiller’s dried grains with solubles) and oil account for between 20% and 30% of gross revenue. If the price of ethanol falls, demand for animal protein (feed) often helps sustain the plant's profitability.

Risks that affect ROI	
Biomass Price	The ROI of maize ethanol is extremely sensitive to the cost of firewood or wood chips for steam production. If the region lacks reforestation, the ROI drops drastically.
Grain Logistics	While sugarcane is "around" the mill, maize can come from far away. Freight volatility and the price of a sack of maize (an international commodity) are the biggest risks for the investor.

The “Flex” Model (The Best of Both Worlds?): Many investors opt for “Flex” units, which attach a maize distillery to an existing sugarcane mill.	
Advantage	It utilizes the sugarcane bagasse boiler, fermenters, and ethanol distillers to process maize during the sugarcane off-season.
Result	The investment is lower than for a "Full” maize plant, and the ROI is accelerated because it utilizes infrastructure already paid for by the sugarcane operation.
Summary: maize/sorghum plants tend to have a **shorter payback period and a higher nominal ROI due to their ability to operate year-round**. However, they often have lower operating margins (EBITDA) than sugarcane in years when sugar prices are high.	

Source: Milanez et al. (2014), Silva et al. (2020), Mvelase and Ferrer (2024), Balai and Yadav (2026).

Table 9. Simplified cash flow projection for a maize bioethanol plant (Milanez, 2018; Chandel et al., 2021), considering a plant with an average processing capacity of 500,000 tons of maize per year, and estimates based on average market prices (maize ethanol at R$ 2.50/L).

Simplified Annual Projection (Estimate)		
Item	**Basic Calculations**	**Value (R$ Millions)**
Total Gross Revenue		**1,560**
(+) Ethanol (Hydrated/Anhydrous)	225 million liters @ R$2.50/L	562
(+) DDGS (Bran)	150 thousand tons @ R$ 1,100/t	165
(+) Maize Oil	9,000 tons @ R$ 5,000/t	45
The Operational Expenditure (**OPEX)**		(615)
(-) Maize (Raw Material)	8.3 million bags @ R$ 60.00	(500)
(-) Biomass/Energy	Wood chips/Eucalyptus	(55)
(-) Inputs, Labor and Maintenance	Enzymes, chemistry and fixed	(60)
EBITDA (Operating Profit)	Revenue – OPEX	157
(-) Depreciation and Taxes (Est.)	~30% of EBITDA	(47)
Estimated Net Profit		110

Feasibility Analysis (Indicators)	
Initial Investment (Estimated capital expenditure - CAPEX)	R$ 800 million (for a plant of this scale).
EBITDA Margin	25.5% (A healthy margin that allows for amortization of capital in the medium term).
Simple *Payback*	Approximately 5.1 years (Investment / EBITDA).
Break Even Point	The project is highly sensitive to the relationship between maize and ethanol prices. If the price of maize rises to R$ 80/sack, without passing the increase on to the fuel price, the operating margin becomes almost zero.

Sensitivity Factors	
Energy Sale	If the plant sells surplus electricity from biomass back to the grid, revenue could increase by 3% to 5%.
Logistics	The cost of transporting DDGS to livestock production regions (feedlots) can impact net profit by up to 10%.

price of ethanol/DDGS (products, “outputs”). Therefore, variations in key costs affect the venture’s final outcome, feasibility, and economic return (Table 10).

A strategic location analysis to maximize ROI in Brazil, focusing on the implementation and functionality of maize bioethanol plants, combined with raw material supply logistics and the business model and scale definition, brings together territorial and resource elements, infrastructure and logistics, and governance to determine the feasibility and opportunity for implementing the agro-industrial venture. Ongoing analyses are based on the “opportunity cost” of the grain and proximity to product consumption hubs, with emphasis on DDGS – for export or as a feed ingredient for use in the local/regional animal protein value chain. (Table 11).

To consolidate the feasibility and opportunity analysis for implementing a biorefinery to produce bioethanol from grain starch (maize/sorghum) in Brazil, it is relevant to integrate CAPEX and OPEX variables with elements relevant to the business’s competitiveness, observed in the Brazilian geographical and territorial reality. Table 12 shows a tactical framework comparing the attractiveness of the three main expansion frontiers for ethanol production from grain starch.

Conclusion

This article analyzes the changes in the Brazilian energy matrix driven by bioethanol production from starchy raw materials, highlighting the “Maize Revolution – the grain that is revolutionizing Brazil and the world” and the expansion of grain sorghum production, notably in the “Brazilian sorghum belt,” associated with the expansion of biorefineries (of the types characterized as “Full” and “Flex”) for processing maize and sorghum, boosting food and energy production. The model integrates ethanol production with co-products such as DDG/WDG and oil, and generates electricity, aligning with the promotion of sustainability through RenovaBio and driving regional socioeconomic development.

A comprehensive analysis of data and trends allows us to conclude that Brazil successfully pursues a bioeconomy of tropical agriculture, grounded in the concepts and operational practices of a differentiated biorefinery for ethanol production. This biorefinery can produce and utilize alternative agricultural raw materials (saccharin and starchy), operating innovative biophysical and chemical processes for the conversion and use of co-products in a sustainable agri-food matrix, with bioenergy efficiency, selecting alternatives based on diversity, adaptation, overcoming challenges, and resilience to promote change with competitiveness and sustainability.

Thus, Brazil is not only adding new raw material alternatives to its energy matrix for ethanol production; the country is also inaugurating a new industrial era, unfolding both in the field and in industry. Bioethanol obtained from grains, starchy raw materials, currently supported by second-crop maize and sorghum, has proven to be a disruptive technology that combines the promotion of energy security (increased supply of biofuel), food production (increased supply of animal protein for human consumption, via the supply of DDG for

Table 10. Variations in main costs and impacts on the economic results of maize bioethanol plants.

Sensitivity Matrix: Maize Price vs. Profitability
Maize accounts for approximately 80% of variable costs. Small fluctuations in the grain market (CBOT or B3) have a significant impact on profit.

Baseline Scenario:	**Maize at R$60.00/sack; EBITDA of R$157 million/year**
Event:	20% increase in maize price (R$100 million). EBITDA falls to R$57 million. *Payback period* jumps to over 12 years.
	20% drop in maize price (R$100 million). EBITDA rises to R$257 million. *Payback period* falls to less than 4 years.
Mitigation Strategy	Plants use financial *hedging* and forward purchase agreements (*barter*) to lock in grain costs and guarantee return on investment - ROI.

The Weight of Biomass (Energy): Unlike sugarcane, which has "low-cost" bagasse, maize requires purchasing fuel to operate the steam boiler.

Impact	The cost of biomass (wood chips or eucalyptus) can represent 10% of Operational Expenditure - OPEX.
Regional Risk	In regions with limited reforestation, the cost of transporting timber can make the operation unfeasible. A 30% variation in the price of biomass impacts the cost of a liter of ethanol by approximately R$ 0.08.

Leveraging with Co-products (DDGS and Oil): Co-products are not just "extras" they are profitability insurance.

Amortization Capacity	On average, the sales of DDGS and Oil recover between 45% and 55% of the value spent on purchasing maize.
Relationship with Animal Protein	If the price of maize rises, the price of soybean meal (a competitor to DDGS) usually rises as well. This allows the mill to increase the price of DDGS, partially offsetting the rise in the raw material cost.

Summary of Cost Impact (Risk Checklist)

Variable	Impact on Profit	Risk Level	Observation
Maize Price	Most High	Critical	It depends on the harvest/weather and the exchange rate.
Price of Firewood	Average	Moderate	It depends on local forestry logistics.
Enzymes / Chemicals	Low	Low	Generally tied to the value of the dollar.
Logistics (Freight)	Medium/High	Regional	It impacts the transport of grains to the plant and the delivery of DDGS co-product.

Conclusion regarding the Actual ROI
Investing in a starch biorefinery is extremely attractive in **grain surplus scenarios** (such as those in the states of Mato Grosso and Goiás), where local maize is cheap due to high export freight costs. In these regions, transforming maize into ethanol and protein (DDGS) "in-house" is the most profitable strategy.

Source: Scholey et al. (2016), Mizik (2021), Scown et al. (2021).

Table 11. Analysis of the selection of location in Brazil for maize bioethanol biorefineries, as a strategy to maximize return on investment (ROI).

Mato Grosso (MT): It is the leading state in terms of volume and cost of raw materials.
MT consolidated its position as the largest national grain producer by 2025, with a 32% share. It is the state with the highest ROI for large-scale plants (the "Full" model).

Advantages of the raw material	The price of maize in cities like Sorriso and Sinop is structurally lower due to high export freight costs, which reduce the price of the raw material "at the factory gate".
Ecosystem	It houses the largest units of Inpasa and FS Bioenergia, which together have a production capacity exceeding 3.5 billion liters.
Goiás (GO): It is the hub for sorghum inclusion and offers tax incentives. Goiás is one of the best states for projects seeking diversification with sorghum, a crop that offers lower planting costs and high climate resistance.	
Strategic Incentive	The state recently implemented an ICMS tax exemption for sorghum specifically to encourage ethanol production.
Demand for DDGS	It has one of the largest cattle feedlots in the country (Fazenda Conforto), guaranteeing an outlet for this co-product.
Mato Grosso do Sul (MS), Minas Gerais (MG) and Paraná (PR): They offer advantages in logistics and access to the domestic market. These states offer a balance between grain supply and proximity to the major fuel-consuming centers in the Southeast.	
Mato Grosso do Sul	In 2026, it consolidated its position as the 3rd largest maize producer in the country, surpassing Goiás. The state offers logistical advantages via waterway and railway for access to the Port of Santos.
Minas Gerais	It possesses significant advantages and a high ranking relative to Brazil: territorial area, population, GDP, cattle herd, growth of agribusiness through cooperatives, number of logistics companies and modernizing agricultural enterprises, with intelligent and creative movements to promote agriculture (such as Central Mineira/Eixo Centro Noroeste MG and the +Sorgo Program in Brazil, coordinated by Embrapa, Sistema Faemg, the State Government and partners – private and public).
Paraná	Ideal location for the cooperative model. Paraná is the second largest maize producer in the country and has the largest number of agro-industrial cooperatives, which reduces supply risk.

Comparative Summary for Investment: Situation and Prospects

State	ROI-Enhancing Factor	Main Advantage	Main Risk
Mato Grosso	Grain Cost	Cheapest maize in Brazil	High cost of biomass (wood) for steam production.
Goiás	Sorghum & Fiscal	ICMS exemption for sorghum	More pronounced climate seasonality
Mato Grosso do Sul	Logistics	Proximity to the markets of São Paulo/Paraná	Strong competition with exports
Minas Gerais	Scale of agricultural production, supply of forest biomass and energy sorghum	Agricultural production is expanding, including first-crop grains. Public-Private Partnership initiatives are underway for science, technology, and innovation.	Modernization of public policies for the agro-environmental agenda; a break from the culture of extensive livestock farming; and the promotion of cooperativism and agro-industry.
São Paulo	"Flex" Plants	Take advantage of the sugarcane ethanol plant's infrastructure.	The most expensive grain in the country.

Strategic Conclusion

To maximize return on investment (ROI), the northern region of Mato Grosso (Sinop/Lucas do Rio Verde) remains quite attractive due to the maize price differential. However, for investors seeking fiscal security and diversification, the southwestern regions of Goiás (Rio Verde), southwestern Bahia, and the central/northwestern territorial axis of Minas Gerais (Sete Lagoas/Curvelo/Três Marias/Patos de Minas and Pirapora/João Pinheiro/Paracatu/Unaí and surrounding areas) present themselves as relevant alternatives for agricultural and agro-industrial expansion, in recognition of the potential of existing natural resources and new incentives for agricultural production, logistics, cooperative and credit systems, and robust demand for grains and livestock.

Source: Silva et al. (2020), Oliveira et al. (2022).

Table 12. Situation and perspectives of a comparative tactical framework of the attractiveness of five main agricultural expansion frontiers considering elements relevant to business competitiveness – grain availability, cost of biomass for energy production, logistics and investment.

Geographic and Territorial Analysis

Region / Hub	Grain Availability	Cost of Biomass (energy)	Outflow Logistics	Investment Profile
Northern Mato Grosso (Sinop / Sorriso)	**Extremely high:** Maize "stuck" due to distance from ports (cheap).	**Critic:** Shortage of eucalyptus; high cost of firewood.	Long distances for ethanol; great for local DDGS consumption.	Giant scale of **"Full"** maize plants (>1 million tons/year).
Southwest of Goiás (Rio Verde / Jataí)	**High:** Large production of maize and sorghum.	**Good:** Region with a forestry tradition and a supply of agricultural byproducts.	Proximity to the markets of São Paulo and Minas Gerais.	Medium sized and **hybrid (maize + sorghum) plants**.
Southern MS/PR (Dourados / Cascavel)	**Medium/High:** Competitive with export (more expensive).	**Excellent:** Large supply of biomass and wood waste.	Excellent logistics (Railroad / Waterway).	" **Flex"** plants or integrated into Agricultural Cooperatives.
Southwest of Bahia	**Medium/High:** large grain production	**Good/Excellent:** biomass production and supply.	Proximity to the Matopiba market and network to access abroad.	Medium sized and **hybrid plants** (maize + sorghum) **plants**.
Central/Northwest Axis of MG	**Medium/High:** High potential for grain production.	**Good/Excellent:** Minas Gerais contains about 1/3 of Brazil's planted forests and has high potential for biomass production, including energy sorghum.	Strategic logistics, with important modes of transport (road and rail). Minas Gerais is a large market and is connected to other relevant markets.	"Full" plants, at different scales, with high potential for the use of maize, sorghum, and forest and grass biomass.

The Energy Challenge: The "Invisible Cost"

Unlike a sugarcane ethanol plant, which is self-sufficient in energy for its operation (through steam production and cogeneration of electricity in boilers that burn bagasse from the sugarcane mills), a maize plant is a consumer of biomass for energy production.

Investment in boilers	Steam-generating boilers account for approximately 15% to 20% of Capital Expenditure - CAPEX.
Territoriality	In Mato Grosso, the cost of biomass can fluctuate, varying by up to 50% throughout the year. In regions like Paraná or the interior of São Paulo, integration with the wood industry reduces the operational risk of biomass shortages for energy production.
Efficiency	Modern plants invest in cogeneration, possessing boilers that produce steam for industrial processes and sell the surplus electricity to the grid, which can represent an additional revenue of R$ 40 million/year in large-scale units.

Logistics of Co-products (DDGS and Oil) Return on investment - ROI is heavily influenced by the plant's ability to sell DDGS without significant logistics (freight) costs.	
"Cattle Belt"	Installing the plant near feedlots (Goiás and Mato Grosso) can eliminate the drying costs associated with DDGS production. In this scenario, WDGS (wet product), despite being highly perishable, can be sold directly, saving the energy expenditure (and cost) of drying at the plant.
Added Value	Maize oil, although a co-product produced in smaller volumes, has simplified logistics and high value as a raw material for the biodiesel industry, functioning as a quick cash generator (weekly liquidity).
Raw Materials: The Rise of Sorghum Grain sorghum is no longer a marginal crop or a "stopgap"; it is becoming a strategic raw material to ensure an adequate rate of return on investment.	
Resilience	In years when the El Niño phenomenon prevails, or during severe drought in the second maize crop, sorghum guarantees the supply to the mill with a production cost 20% to 30% lower than that of maize.
Plant Use	Biomass sorghum can also be used as fuel to operate the plant's own boiler, closing a cycle of energy self-sufficiency in regions where wood is expensive.
Summary for Decision Making	
Scenario of Greater Profitability	To install an industrial plant for the production of bioethanol from grain starch in GO, MS and MG, with technology to process maize and sorghum, integrated with a cattle feedlot owned by the company or by partners (to use wet DDGS) and with a long-term contract for the supply of biomass (eucalyptus, energy sorghum, residues) for energy production in the boilers (which generate the steam and electricity necessary for the operation of the industrial process and a surplus of electricity to be sold to the grid).

Source: Martinkus et al. (2018), Colussi and Schnitkey (2022), Oliveira et al. (2022).

animal feed composition) and environmental sustainability (preservation of forests through sustainable agricultural intensification).

The biorefineries that produce ethanol in the interior of Brazil represent the materialization of the circular bioeconomy, on an industrial scale, in the agroenergy sector. They take advantage of natural processes that convert, through photosynthetic processes and complements in the food chains of trophic levels, sunlight (primary and intense electromagnetic energy in tropical zones) into stored chemical energy (in structural carbohydrates – in lignocellulosic biomass of cellulose, hemicelluloses and lignin, and in soluble and transport carbohydrates – starch, sugars).

In the case of ethanol production from starchy raw materials, the energy stored in grains (maize and grain sorghum) during the "safrinha" as starch is converted into ethanol and low-carbon co-products with high global demand. However, the functionality and success of this biorefinery model imposes on the Brazilian State the challenge of strengthening and modernizing a National Bioenergy Plan as a firm legal framework to encourage public-private alliances and partnerships and unlock the implementation of logistical infrastructure (Ferrogrão / Ethanol Pipeline), otherwise the development of one of the most dynamic and promising sectors of the national economy will be stifled.

The feasibility of constructing the Ferrogrão railway project depends on the Brazilian Supreme Court, the Supremo Tribunal Federal (Cordeiro, 2026), which has included on its docket since 2025 the constitutional validity of Law 13,452/2017. This law reduced the area of the Jamanxim National Park, in the state of Pará, to enable the construction of the Ferrogrão, which is designed to connect Pará to the state of Mato Grosso and facilitate the transport of agricultural production. In 2021, Justice Alexandre de Moraes granted an injunction suspending the effectiveness of the law, as well as all processes related to the Ferrogrão within the National Land Transport Agency (ANTT), the Ministry of Infrastructure, and the Federal Court of Accounts (TCU). In 2023, upon granting a request from the Office of the Attorney General (AGU), the Justice authorized the resumption of studies and administrative processes regarding the railway, while conditioning any physical execution on judicial authorization from the STF. The analysis of the matter remains under review by the Supreme Court.

The profile of the Brazilian biorefinery to produce bioethanol and co-products presents both traditional and new models, in "Full" and "Flex" arrangements, and is synthesized in characteristics of the availability and prices of raw materials – sugarcane and grains, territorial logistics, and scale for current and future markets (Table 13).

Table 13. The Profile of the Brazilian Biorefinery to Produce Bioethanol and Co-products: Synthesis of industrial models and technical, managerial and market characteristics.

Feature	Traditional Model (Sugarcane Mill)	New Model (Grain Biorefinery)
Operation	Seasonal (Harvest/Off-season - 200 days)	Continuous (365 days/year)
Raw material	Sugarcane (Perishable - 48h)	Maize/Sorghum (Storable - 365 days)
Main Products	Ethanol, Sugar, Bioelectricity	Ethanol, DDG (Protein), Oil, Bioelectricity
Integration	Agricultural (Own and Third-Party Sugarcane Fields)	Agricultural (Own and Third-Party Planting of Maize/Sorghum) and Livestock (Feedlot/Feed)
Impact on the Soil	Long-Term Occupation (5-6 years)	Second Crop (Temporary Occupation / Intensification)
Climate Dependence	High (Drought ruins the harvest and disrupts industry operations)	Medium (Grain and sorghum stockpiles mitigate the risk)

Source: Martinkus et al. (2018), Colussi and Schnitkey (2022), Oliveira et al. (2022).

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