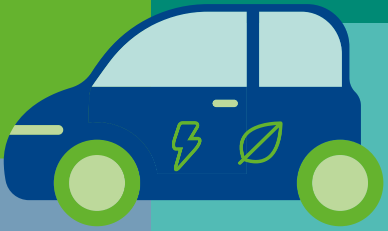
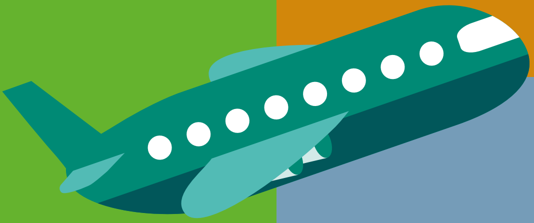


BIOETHANOL

FAST TRACK TO MOBILITY DECARBONISATION



Coordination

cgee
Center for Strategic Studies and Management
Science, Technology and Innovation

BNDES
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Foreword

As we move towards the second quarter of the 21st century, the international community is bound to reflect on the shared values that hold us together, in a century that will test our human ability to adapt, and innovate, and build a common future.

Now, not only do we hear about climate risks, but we also experience the climate urgency. Climate change has arrived at our doorsteps, affecting our ecosystems, cities, and daily lives. We should avoid the dangerous path in which, in both developed and developing countries, those who can afford it isolate themselves behind climate-resilient walls as the poor are increasingly exposed.

The time to act, all hands-on-deck, is now.

The energy sector accounts for approximately 75% of global greenhouse gas emissions. However, almost 700 million people still lack access to basic energy services, and the surge in energy demand as countries develop (and get warmer) will have to be met by clean energy. Just, affordable, and inclusive energy transitions are essential to achieve sustainable development goals and net-zero greenhouse gas emissions by or around mid-century.

The UAE consensus and the Outcome of the first global stocktake (GST) of the Paris Agreement called upon us to accelerate the global energy transition and gave us guidance on what should be done. Now we need to consider how to do it.

The COP30 spirit of *mutirão* is meant to bring people together—governments of all levels, international organizations, academia, the private sector, think tanks, civil society—to propose practical, scalable solutions to promote meaningful implementation of the GST goals.

Imbued with this spirit, the COP 30 Action Agenda seeks to streamline and integrate past and future efforts to accelerate implementation by creating an inclusive framework for all actors to connect and work in unison whilst regularly taking stock of the progress achieved. The Action Agenda Axis 1, on transitioning energy, industry, and transport, invites the global community to present solutions for the objectives of tripling renewables and doubling energy efficiency; accelerating zero- and low-emission technologies in hard-to-abate sectors; ensuring universal access to energy; and transitioning away from fossil fuels, in a just, orderly, and equitable manner.

It so happens that one of the most sustainable solutions has been in use in Brazil for 50 years. The Brazilian experience with ethanol has avoided millions of tons of emissions; is technologically mature; uses existing infrastructure; generates jobs; recovers degraded land; and, most importantly, can be shared with other regions and countries where fossil fuels imports generate dependency and overload budgets, and where electrification is not a short-term solution because of high costs and lack of infrastructure. Many developing and resource-rich countries have untapped potential to produce and use biofuels, but depend on a push towards science-based, inclusive, and well-structured policymaking.

The *Bioethanol—Fast track to mobility decarbonisation* book is a formidable initiative that embodies the collaborative essence of COP30. The book shares the best available knowledge in science and policymaking to address one of the major causes of the climate crisis. By detailing Brazil's policy experience with biofuels, the book will contribute to help others promote adequate planning, capacity-building, and institutional governance towards their energy transitions goals.

Understanding the use of bioethanol means opening our minds to the sustainable use of natural resources to tackle the climate crisis more widely. Recognizing the potential of a sustainable connection between energy and agriculture, a pillar of human civilization, may help us face the urgent challenges of environmental degradation, diminished biodiversity, global warming and persistent poverty, and associated injustices. Sustainable biofuels can be a central pillar of the bioeconomy, increasing energy access, promoting agricultural modernization, enhancing soil quality, and generating income for local populations.

The fight against climate change cannot disregard developing countries' specific needs and particular realities. Bioenergy is not a lesser alternative. It may, in fact, be the key to energy transitions, sustainable development in different regions of the planet, as we collectively fight climate change.

I hope that this book might become a bridge to connect the international community to some of the most ingenious solutions offered by the Global South to address our shared challenges.

Ambassador André Aranha Corrêa do Lago
Designated President for COP30

Presentation

The transport sector is responsible for 20% of energy-related global greenhouse gas (GHG) emissions, which, in turn, account for around 75% of total GHG emissions. Decarbonising this sector, thus, is one of the main challenges on the environmental agenda.

The clean, sustainable, just, affordable, and inclusive energy transitions the world urgently needs are only possible through neutral, integrated, and agnostic approaches to technology. Countries should be able to adopt solutions based on their domestic realities and available resources. In other words, we cannot and must not discriminate in principle among alternatives. When choosing options for the generation of clean energy, it is fundamental to take local conditions into account and fulfil sustainability premises, with low emissions and accessible prices.

The transition to a sustainable low-carbon economy worldwide must be an inclusive process that considers the need for job creation, respects diversity and contributes to social development, leaving no one behind. At the same time, it must be an opportunity for the development of new industries through technological innovations and investment attraction. Creating these opportunities, particularly in developing countries, will contribute to the reduction of global inequalities. Some 700 million people still lack access to basic energy services. The surge in energy demand as countries develop will have to be met by clean energy. We can only address this issue by using all technologies and sources that will enable emissions reductions.

Bioenergy is the "overlooked giant in renewable resources". Yet its share is 50%, as much as hydro, wind, and solar combined.[1] Despite currently being the most developed and cost-effective alternative to fossil fuels, biofuels represent only 3% of renewables in transport. Their production has been insufficient to achieve our net-zero and sustainable development goals. With increasingly sustainable production, bioethanol, for instance, has one of the smallest carbon footprints in the world, with the capacity to reduce emissions by up to 90% when compared with gasoline. It is a drop-in technology that

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[1] IEA (2018), **Renewables 2018**, IEA, Paris. https://www.iea.org/reports/renewables-2018.

can be implemented comparatively quickly, using existing infrastructure. The world has over two billion combustion engine vehicles that could be far less polluting if they ran, at least partially, on biofuels.

In this scenario, developing countries hold the greatest potential for expansion in the production and consumption of sustainable biofuels. There is, however, an urgent need for technology, public policy, experience, and knowledge to unlock this potential and expand production and distribution adequately and sustainably at a sufficient rate to yield significant benefits.

Over the last five decades, Brazil has built significant experience in this field, which has been shared with a number of countries through bilateral technical cooperation and capacity-building. The use of bioethanol and biodiesel in the transport sector has avoided the consumption of 3.3 billion barrels of oil and over 1.6 billion tonnes of CO_2 emissions since 1975 in Brazil, while contributing to the improvement of socio-economic indicators in productive regions, providing greater access to energy in rural areas, and strengthening food security.

Starting with experimental bioethanol blending mandates in the 1930s, the Brazilian government's experience with bioethanol for consumers gained traction in 1975 with the Pro-Alcohol Programme. In 1979, vehicles capable of using pure bioethanol (E100) were launched, and in 2003, flex-fuel engines allowing any bioethanol-gasoline blends were introduced in the Brazilian fleet of passenger vehicles enabling the use of pure bioethanol (E100) in cars produced with that technology. Some 85% of the Brazilian fleet (approximately 33.7 million cars) is now flex-fuel. Shortly after, in 2005, the Biodiesel Law introduced biodiesel blending in diesel. In 2017 came the National Biofuels Policy (Renovabio) with particular focus on emissions reduction, based on decarbonisation targets, certification of biofuel production, and decarbonisation credits.

In 2024, President Lula sanctioned the Fuel of the Future Law, which elevated minimum and maximum blend rates for ethanol (from 27.5% to 35%) and biodiesel (from 13% to 25%). It also created programmes for sustainable aviation fuels—establishing mandatory emissions reductions in the domestic aviation sector—green diesel, natural gas, and biomethane; and regulated CO_2 capture and storage and the biomethane sector. As a result, since August

2025, Brazilian gasoline contains 30% ethanol (E30), while diesel contains 15% biodiesel (B15).

The Brazilian experience demonstrates how bioenergy can be a sustainable, low-cost, and competitive solution for decarbonisation efforts. It also shows how the production and use of sustainable biofuels can be a major contribution from the Global South to global energy transitions and sustainable development, by enabling the immediate decarbonisation of the transport sector, generating employment and reducing dependency on fossil fuels.

*

Although there is no universal multilateral regime for energy, the issue has gained significant international momentum due to the enormous economic and geopolitical relevance of the energy sector, heightened in recent years by the imperative of energy transitions in the context of climate change. Internationally, the treatment of the issue takes place in a fragmented manner, across various organisations, in instances such as the G7, G20, and BRICS, in regional forums and in bilateral contexts.

Wary of the weight of energy production and consumption in GHG emissions, in November 2023, the first Global Stocktake (GST) of the Paris Agreement launched an unprecedented call. At COP28, in Dubai, countries committed to triple global renewable energy capacity, double the average annual rate of improvement in energy efficiency, and to transition away from fossil fuels in energy systems in a fair, orderly and equitable manner, among other commitments.

Brazilian diplomacy has brought biofuels to the forefront of discussions on the implementation of these commitments, in bilateral, regional, and multilateral contexts. Promoting cooperation between experts, legislators, policymakers, regulators, and industry representatives at all levels allows countries and institutions to learn from each other's experiences and best practices, and to improve regulation, policy, production, efficiency, and sustainability, thereby contributing to a stable biofuels market, both domestically and internationally.

In 2024, under Brazilian presidency, G20 leaders "[underscored] the crucial role of technologically neutral, integrated and inclusive approaches to develop and deploy a variety of low-emitting energies, sustainable fuels and technologies,"[2] with a view to accelerating the energy transition, particularly in hard-to-abate sectors.

The 2024 Joint Statement on Sustainable Bioenergy for Climate and Development Goals[3] stresses that sustainable bioenergy can contribute to energy security, clean energy access, rural development, increased agricultural productivity, improved farmer incomes, job creation, gender equality, responsible industrial development, poverty eradication, and climate change mitigation and adaptation strategies.

Initiatives such as the Global Bioenergy Partnership (GBEP), the Biofuture Platform (BfP), and the Global Biofuels Alliance (GBA) show how country-led initiatives created by dedicated policymakers can spread their wings and make an impact in the context of an inevitably growing biofuels market, by identifying avenues for cooperation to promote sound, science-based and cooperative policymaking worldwide, reaching the countries and regions that need it most.

Today, more than 70 countries have already established the blending of different percentages of ethanol into gasoline. India, for example, has reached E20 faster than originally expected and has managed to reduce emissions, improve air quality, and reap economic benefits from this new industry. It now moves forward towards improving sustainability and developing flex fuel technology to expand bioethanol use.

The commitments to reduce emissions made by members of the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO) shed light on the importance of sustainable biofuels for long-term emissions reduction in these sectors, in which electrification and new energy sources require more time to deliver long-term sustainable solutions. In this context, however, there is a clear scenario of growing regulatory fragmentation. This creates uncertainty among

---

[2] G20 Rio de Janeiro Leaders' Declaration, 2024. https://www.gov.br/planalto/pt-br/media/18-11-2024-declaracao-de-lideres-g20.pdf.

[3] The Statement, which follows this Presentation, was developed by a cross-initiative coordination group on bioenergy convened by the Global Bioenergy Partnership (GBEP). The Statement was issued by: Clean Energy Ministerial Biofuture Platform Initiative; Food and Agriculture Organization of the United Nations (FAO); Global Bioenergy Partnership (GBEP); International Energy Agency (IEA); IEA Bioenergy Technology Collaboration Programme; International Renewable Energy Agency (IRENA); United Nations Environment Programme (UNEP); United Nations Economic Commission for Europe (UNECE); and the United Nations Industrial Development Organization (UNIDO).

stakeholders, and high transaction and compliance costs, particularly for producers of sustainable fuels in developing countries. Comparability, agnosticism, technological neutrality, and context-specific approaches to carbon accounting are essential if all low-emission alternatives are to be considered and scaled.

An outcome of the joint effort of Brazilian Ministries of Foreign Affairs (MRE), of Mines and Energy (MME), and of Science, Technology and Innovation (MCTI), the Brazilian Development Bank (BNDES), and the Center for Management and Strategic Studies (CGEE), *Bioethanol—Fast track to mobility decarbonisation* helps spread the word about the vast potential of international cooperation for the promotion of biofuels. Grounded in open knowledge-sharing and horizontal cooperation, the book provides detailed technical and scientific data to support and inspire policymakers to consider a technological pathway that can help the world achieve Fast, Accessible, Inclusive and Renewable (FAIR) energy transitions. It brings together renowned authors and specialists from academia, the private sector, and the Brazilian government to detail the technological, socio-economic, and environmental attributes of bioethanol.

The first part of the book explores the topic of modern sustainable bioenergy. The authors present the fundamentals of bioenergy; the use of bioethanol as a fuel for mobility; and delve into the processes and science behind bioethanol production and the advanced technologies used to produce bioenergy and biomaterials from ethanol. The second part takes readers through the history and development of the Brazilian experience with sustainable bioenergy, including the sugarcane refinery industry and the sustainability of biofuel production. Finally, the authors explore the global perspectives for sustainable biofuels, their potential, and impacts.

*

A significant increase in biofuel production is needed to reach global net-zero emissions targets,[4] transition away from fossil fuels and accelerate zero- and low-emission technologies in hard-to-abate sectors. It is up to international actors and stakeholders to develop regulations, seek standards harmonisation, and promote coordination to improve efficiency, production,

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[4] IEA (2023), **Tracking Clean Energy Progress 2023**, IEA, Paris. https://www.iea.org/reports/tracking-clean-energy-progress-2023.

and innovation in this field. International knowledge-sharing and cooperation have already delivered significant results and remain a formidable tool to make sustainable development goals achievable and the fight against climate change one we can collectively win.

Department of Energy of Ministry of Foreign Affairs of Brazil

Joint Statement on Sustainable bioenergy for climate and development goals

In consideration of the persistent debates about what role bioenergy should play in support of climate and sustainable development goals, and acknowledging the most recently available scientific evidence, the undersigned organizations issued the following joint statement:

> *Sustainable bioenergy is a component of the bioeconomy. It can be produced from biomass resources in multi-functional, integrated agriculture, forestry, fisheries and aquaculture systems, along with food, feed and/or bio-based products, from biogenic waste and residue streams, or as a co-product of ecosystem management.*
>
> *Sustainable bioenergy can be produced with energy-efficient and low-emission technologies, and is derived from sustainable biomass resources.*
>
> *Sustainable bioenergy can make a crucial contribution to keep global warming below 1.5°C by the end of the century. It plays a unique role in just and inclusive energy transitions, and is especially important for sectors and regions where other decarbonisation options are costly or not yet available.*
>
> *Biomass and its bioenergy derivatives are versatile, storable and dispatchable; they can replace fossil energy and complement variable renewables and other low-carbon options in transport, power and heat production, industrial processes and clean cooking, thereby enhancing resilience in the energy system.*
>
> *Sustainable bioenergy can contribute to energy security, clean energy access, rural development, increased agricultural productivity, improved farmer incomes, job creation, gender equality, responsible industrial development, poverty eradication, and climate change mitigation and adaptation strategies.*
>
> *Benefits and trade-offs of bioenergy systems depend on context, scale, and local needs and priorities. Good governance of bioenergy systems is key to maximize opportunities and minimize risks of negative impacts, and to ensure an integrated approach that aligns with the Sustainable Development Goals.*

> *Good governance builds on evidence-based assessment of environmental, economic, social and political factors, and safeguards food and energy security, climate justice, biodiversity stewardship, land and water rights and local development priorities. It follows the principles of nature-based solutions,[5] including local stakeholder engagement, and free, prior and informed consent. Recognized norms for quality and sustainability can facilitate investment, fair trade, monitoring and verification.*
>
> *Through good governance, sustainable bioenergy addresses the risks related to the land and resources used for its production and the potential impacts on food security, natural ecosystems and carbon stocks,[6] as well as the challenges in managing equity and justice, and achieving economic competitiveness and affordability.*

This statement was developed by a Cross-Initiative coordination group on bioenergy convened by the Global Bioenergy Partnership (GBEP). The Statement was issued by:

Clean Energy Ministerial Biofuture Platform Initiative
Food and Agriculture Organization of the United Nations (FAO)
Global Bioenergy Partnership (GBEP)
International Energy Agency (IEA)
IEA Bioenergy Technology Collaboration Programme
International Renewable Energy Agency (IRENA)
United Nations Environment Programme (UNEP)
United Nations Economic Commission for Europe (UNECE)
United Nations Industrial Development Organization (UNIDO)

June 20, 2024.

Available at:

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[5] United Nations Assembly Resolution on nature-based solutions for supporting sustainable development (UNEP/EA.5/Res.5).

[6] As discussed in IPCC, 2019. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (P.R. Shukla, J. Skea, E. Calvo Buendia, V. et al. [eds.]).

List of figures, charts, graphs and tables

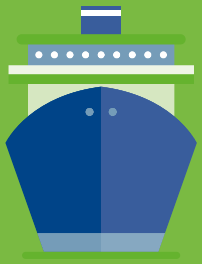
Figures

Charts

Graphs

Tables

Contents



Part 1

THE MODERN SUSTAINABLE BIOENERGY

Bioenergy represents one of the most important forms of solar-derived energy, offering substantial potential for application in modern society. The following chapters present the fundamentals of biomass production and conversion into energy, emphasising its development as a renewable energy source. Technical aspects of bioethanol use in mobility are discussed, along with the main production pathways—particularly those based on sugarcane and maize. In addition, advanced technologies to produce bioenergy and biomaterials are explored, with potential to apply in diverse national contexts.

1.

Bioenergy and biofuels

Luz do sol
que a folha traga e traduz
em verde novo
em folha, em graça
em vida, em força, em luz…

Sunlight
that the leaf swallows and translates
into new green,
into leaves, into grace,
into life, into strength, into light...

Caetano Veloso,
Luz do Sol (*Sunlight*), our translation.

The conversion of solar energy into chemical energy that plants carry out during photosynthesis configures one of the most fascinating phenomena in nature. Plants illuminated by the sun absorb carbon dioxide from the atmosphere and produce biomass, releasing oxygen, which is essential for the life of animals and humans. Moreover, since the beginning of humanity, its symbiosis with the plant world has ensured the supply of food, energy, and wide-use feedstock, enabling the evolution of standards of comfort and economic productivity over millennia. Using the energy of timber, our ancestors developed ceramics and could replace stones with metals.

After a brief interval in recent centuries, in which fossilised solar energy—in the form of coal, oil, and natural gas—began to be extensively explored and used, the energy production of plants has returned to be highlighted in new meanings and forms. Capable of mitigating serious issues in the local and global environment, photosynthetic energy brought a new dynamic to the agro-industrial world and provided an effective alternative to the necessary evolution of modern industrial society toward a more sustainable and rational energy context.

Without claiming to be the exclusive solution, the capture and storage of solar energy in plants can play a prominent role in building an energy future of nations. As prophesied by Ignacy Sachs:

> *Bioenergy is just one part of a broader concept of what is called sustained development, a concept that is based on the tripod biodiversity, biomass and biotechnology and that can serve as a lever for the place that biomass may represent in the coming decades.* (Sachs, 2007)

This initial chapter includes basic definitions and concepts, such as the basic principles of photosynthesis, and describes the evolution of modern bioenergy, describing the production and consumption of bioenergy vectors in Brazilian markets—a good example of a tropical country in which bioenergy has always played a prominent role—and in global markets, in which bioenergy has attractive perspectives.

1.1. Bioenergy foundations

In its most rigorous definition, energy constitutes the capacity to promote change, which occurs in many forms—such as thermal energy, electric energy, and chemical energy—and always represents a potential for transformation, whether natural or determined by humans. Chemical reactions provide chemical energy, by which compositional changes occur, converting reagents into products, usually with heat release. For example, chemical energy is available in food and fuel, being used in the vital processes of animals and humans and in vehicles and industrial processes.

A particular form of chemical energy is **bioenergy**, which can be defined as any type of energy derived from the several ways in which the accumulated chemical energy becomes available by recent photosynthetic processes. In general, **biomass** refers to the natural resources that include bioenergy and can be directly used or processed into more refined and suitable bioenergetic forms for final use. Examples of biomass-based bioenergy include firewood and bagasse for heat and power generation, charcoal, biogas from the anaerobic decomposition of organic and agricultural waste, as well as crops for **liquid biofuels**, such as bioethanol and biodiesel, and **bioelectricity**, generated by burning fuels such as bagasse and firewood.

To facilitate the understanding of bioenergy and its great diversity, the United Nations Food and Agriculture Organization (FAO) proposed a unified terminology of bioenergy (FAO, 2004) that considers the origin of the several types of biomasses and the condition of the product used as a bioenergetic resource in relation to its production chain.

CHART 1. Unified terminology of bioenergy

		WOODY BIOMASS	HERBACEOUS BIOMASS	BIOMASS FROM FRUITS AND SEEDS	OTHERS (INCLUDING MIXTURES)
		Woodfuels	**Agrofuels**		
Energy crop	Direct	• Energy forest trees • Energy plantation trees	• Energy grass • Energy whole cereal crops	• Energy grain	
By-products		• Thinning by-products • Logging by-products	Crop production by-products: • Straw • Stones, shells, husks		• Animal by-products • Horticultural by-products • Landscape management by-products
	Indirect	• Wood processing industry by-pro-ducts • Black liquor	• Fibre crop processing by-products	• Food processing industry by-products	• Biosludge • Slaughterhouse by-products
End use materials	Recovered	• Used wood	• Used fibre products	• Used products of fruits and seeds	• Municipal by-products • Kitchen waste • Sewage sludge

Source: Adapted from FAO (2004).

The biomass sources for bioenergy production are diverse and can be processed by various technological routes, resulting in solid, liquid, and gaseous biofuels. In this broad context, they range from traditional bioenergy systems, such as primitive cooking with firewood (still in use by millions of poor families in many countries) to modern bioenergy uses, in which liquid biofuels stand out in meeting energy demand in the transport sector for their advantages in logistics and end use with reduced fossil carbon emissions.

Despite its diversity in primary resources, energy vectors, and applications, bioenergy is not always listed as a renewable form of energy (which it is), possibly due to its precursor character as all energy sources used by humanity. Moreover, while firewood is the predominant form of energy in many developing countries, this biomass also constitutes the main primary source of energy in several industrialised countries. Worldwide in 2020, biomass accounted for 9% of all electricity, 96% of useful heat, and 90% of renewable energy used in transport (WBA, 2023).

Global bioenergy production has grown significantly in recent decades with the implementation of modern bioenergy systems that sustainably produce and convert biomass employing efficient processes and innovative technologies into final energy vectors such as electricity and liquid biofuels (see Table 1) (WBA, 2023).

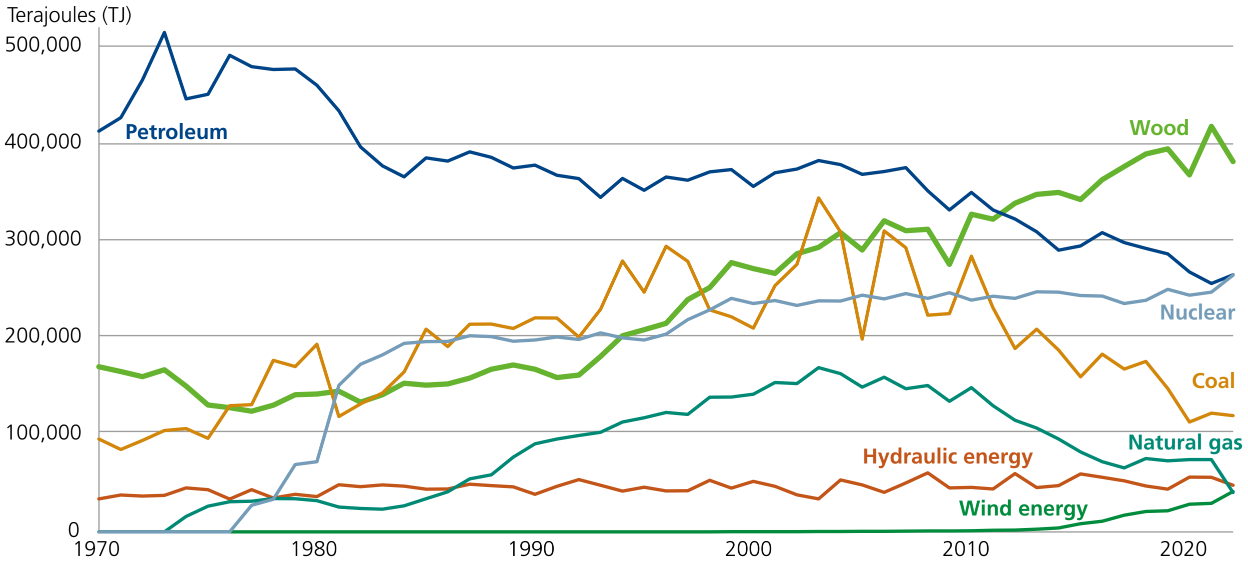
TABLE 1. Global production of biofuel and electric energy via biomass in 2000 and 2020

PRODUCED BIOENERGY	PRODUCTION 2000	PRODUCTION 2020	Δ% (2020/2000)
Liquid biofuel	0.56 EJ	2.56 EJ	457%
Biogas	0.28 EJ	1.46 EJ	521%
Electric energy via biomass	162 TWh	685 TWh	422%

Source: Prepared by the authors based on WBA (2023).

Finland is a country where bioenergy is highly relevant, given its high energy consumption coexisting with less favourable climatic conditions for biomass production. Nevertheless, based on forestry and efficient processes, the participation of bioenergy in the Finnish energy matrix has evolved remarkably since the 1970s, enabling an effective energy transition. While in 1990, oil consumption represented more than twice the consumption of wood for energy purposes, since 2012, because of climate and energy policies, this biomass became the main source of energy, reaching 33% of the total energy consumption in 2022, a development associated with a significant reduction in the consumption of coal, oil, and natural gas, as shown in Graph 1 (OSF, 2024).

GRAPH 1. Evolution of the consumption of energy sources in Finland

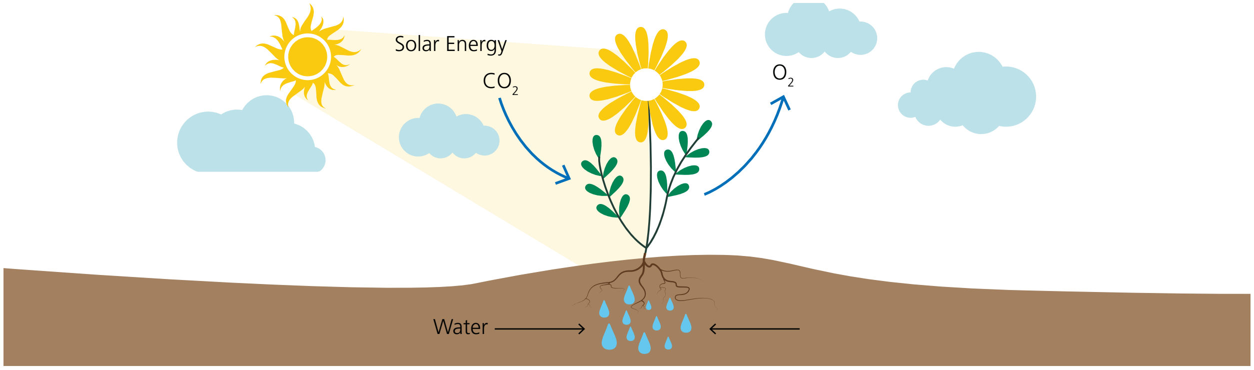


Source: Prepared by the authors based on OSF (2024).

1.2. Photosynthesis

The production of biomass by photosynthesis essentially depends on solar energy, water (H_2O), and carbon dioxide (CO_2), and occurs within plant cells in complex biochemical photosynthetic cycles. In the 1950s, Melvin Calvin (1911-1997) pioneered this process, showing that sunlight falling on leaves decomposes water, releasing oxygen (O_2) and combining hydrogen (H_2) with carbon dioxide absorbed from the atmosphere to form sugars, which form the base of all biomass diversity and its applications, such as biofuels. This discovery showed that the oxygen we breathe, rather than coming from CO_2, stems from water. For this formidable work, Calvin received the Nobel Prize in Chemistry in 1961.

FIGURE 1. The process of photosynthesis



Source: Prepared by the authors.

In short, photosynthesis reactions can be represented by the following expression, in which water and carbon dioxide combine to form a molecule of glucose, a simple sugar, and oxygen.

$$6\ H_2O + 6\ CO_2 \rightarrow C_6H_{12}O_6 + 6\ O_2 \qquad (1)$$

In this reaction, in terms of energy, the formation of 1 kg of sugar corresponds to the fixation of about 17.6 MJ (megajoules) of solar energy, equivalent to about half a litre of gasoline. According to the mass balance, the synthesis of 1 kg of glucose consumes about 0.6 kg of water and 1.4 kg of carbon dioxide, releasing 1 kg of oxygen to the atmosphere. This amount of water represents only the portion used to form the sugar, during their growth and especially during photosynthesis, plants need volumes of water hundreds of times above the amount fixed in the plant product to maintain their temperature by evapotranspiration. Just as we need to sweat when we exercise to maintain our body temperature, plants evaporate great amounts of water to maintain their temperature during photosynthesis.

A relevant parameter for bioenergy systems is the agricultural productivity of different crops, which depends on the efficiency of photosynthetic processes converting solar energy into chemical energy and storing this chemical energy in biomass. In recent decades, significant scientific efforts following the seminal work of Calvin have explained the biochemical mechanisms that enable plants to synthesise sugars and other chemicals, establishing carbon fixation routes and identifying their different phases in reaction sequences with several bifurcations and unstable compounds up to the formation of stable substances in more than one type of photosynthetic cycle.

The most interesting photosynthetic cycles are the Calvin cycle (or C3 cycle) and the Hatch-Lack cycle (or C4 cycle), in which the molecule of the first stable product contains three (phosphoglyceric acid) or four carbons (such as oxaloacetate, malate, and aspartate), respectively (Hall and Rao, 1999). While most known plants use the C3 cycle, some tropical grasses, such as sugarcane, maize, and sorghum, employ the C4 cycle. Table 2 compares these photosynthetic cycles (Janssens *et al.*, 2007).

TABLE 2. Plant performance parameters for photosynthetic cycles

CHARACTERISTIC	C3 SPECIES	C4 SPECIES
Transpiration rate (kg of evaporated water/kg of synthetised biomass)	350 – 1000	150 – 300
Ideal temperature for photosynthesis (°C)	15 – 25	25 – 35
Photosynthesis location	The whole leaf	External part of the leaf
Response to light	Saturated for average radiation	Unsaturated under elevated radiation
Average productivity (t dry mass/ha.harvest)	~ 40	60 – 80
Climate aptitude	Tropical	Tropical
Examples	Rice, wheat, soy, all fruitful oilseeds, and most known vegetables	Maize, sugarcane, sorghum, and other tropical grasses

Source: Prepared by the authors based on Janssens *et al.* (2007).

This distinction is important for the development of bioenergy systems due to the significant productivity difference between these cycles, which favours the C4 cycle as it has a high photosynthetic saturation rate (absorbs more solar energy), no photorespiration loss, highly efficient water use (transpiration ratio), higher salt tolerance, and low a CO_2 compensation point (*i.e.*, it responds better under lower concentrations of this gas). In summary, it can be said that plants with C4 cycle are generally the most suitable for bioenergy production.

The global significance of photosynthesis in energy terms is worth assessing. Of the solar radiation incident on Earth—178,000 TW (terawatt or one billion kilowatts)—estimates suggest that about 180 TW, or 0.1%, is used in photosynthetic processes, whether natural or promoted by humans. Thus, around 114 billion tonnes of biomass are produced annually on a dry basis, corresponding to about 1.97 million EJ (exajoule or one trillion kilojoules), which is equivalent to 314 trillion barrels of oil, about eight thousand times the current global consumption of this fossil fuel. In this context, the average efficiency of solar energy assimilation is below 1%, although some higher performance plants, such as sugar cane, can reach 2.5% annually on average. Naturally, these values serve only as a reference for understanding the energetic magnitude of photosynthesis, making it pointless to imagine bioenergy as a substitute for all forms of energy supply. As noted, such plant growth occurs especially in native tropical formations, and estimates suggest that agricultural activities account for about 6% of this total (Smil, 1991).

1.3. Plant productivity factors

The fundamental condition to produce biomass and thus bioenergy consists of the availability of solar radiation, water, and carbon dioxide. Carbon dioxide is the least problematic of these basic production factors for plants, as it is well distributed in the atmosphere in sufficient concentrations. However, the concentration of CO_2 in the atmosphere has significantly increased, mainly due to the intensive use of fossil fuels, leading to an increase in the greenhouse effect in the atmosphere of the Earth and worrying climate changes, which have justified international agreements aimed at decarbonizing the energy sector and, more broadly, the global economy. Thus, biofuels have two important advantages: their use can reduce fossil carbon emissions into the atmosphere and potentially favour biomass production (within limits and for some species) due to the greater availability of carbon dioxide in the atmosphere.

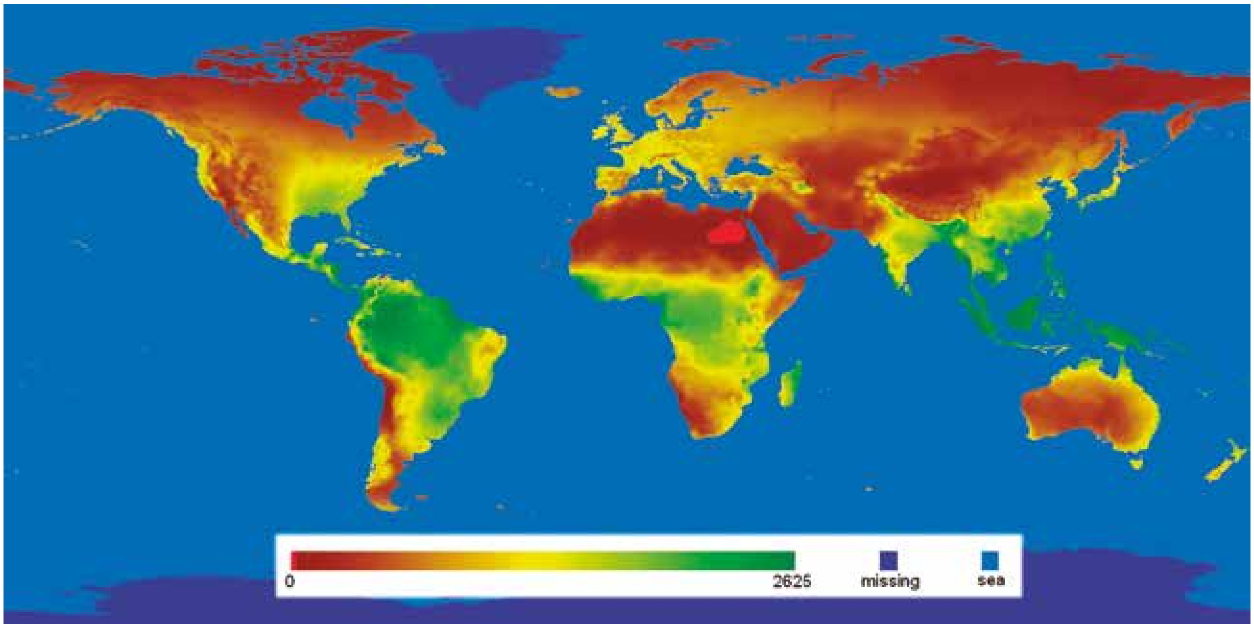
Photosynthesis occurs by the absorption of light by chlorophyll within specific bands of the solar spectrum, especially wavelengths from 400 to 700 nm (nanometres), the red colour region. In plant physiology, this range is called photosynthetically active radiation, which corresponds to approximately 50% of all solar radiation. Regarding the availability of solar radiation, the primary factor is latitude, which means that tropical regions receive more solar energy than those in higher latitudes. According to the Brazilian Solar Energy Atlas, an area of one square meter from 10° to 15° south in Northern Brazil receives, on average, 18.0 MJ/day, whereas at a latitude from 20° to 25° in Southern Brazil, the same area receives 16.6 MJ/day, around 8% less energy (INPE, 2017). Also associated with latitude, ambient temperature is another factor that directly influences photosynthesis. Within limits, higher temperatures favour bioenergy production, reinforcing the advantage of the hottest regions on the planet regarding this matter.

Water also is an essential factor for photosynthesis, constituting, in fact, the primary limiting factor for plant production. The reduced availability of freshwater resources and their heterogeneous distribution across continents constitute one of the greatest challenges for the development of many nations. Extensive sunny areas in semi-arid regions may scarcely contribute as a source of biomass without significant volumes of water for irrigation, implying high costs and energy expenditures that often make bioenergy production unfeasible.

With greater importance in Asia, where countries such as India and Pakistan currently irrigate around 40% of their cultivated areas. Irrigation currently consumes almost 70% of available water resources worldwide and accounts for around 40% of agricultural production, making access to water a topic of enormous priority (UNESCO, 2021). Moreover, climate change, resulting from the increasing greenhouse effect on our planet, tends to significantly alter rainfall and water regimes, increasing the risks of extreme phenomena such as droughts and floods that hinder plant production. Fortunately, some tropical regions, especially in South America and Africa, have sufficient water availability, enabling agricultural production to be promoted with less dependence on irrigation.

Net primary productivity is a parameter that can estimate the theoretical potential of photosynthesis to produce biomass, which represents the maximum possible value for plant production under the local temperature, water availability, and solar radiation, evaluated in grams of dry matter produced over a year per square meter of vegetable leaf exposed to the sun. As the areas in green tones in Figure 2 indicate, the humid tropical regions of Africa, Asia, and Latin America have the highest theoretical biomass productivity, constituting the most favourable contexts for producing bioenergy in harmony with the local lush forests and agriculture. In any case, it is essential to ensure the availability of water resources.

FIGURE 2. Biomass net primary productivity (dry g/m²/year)



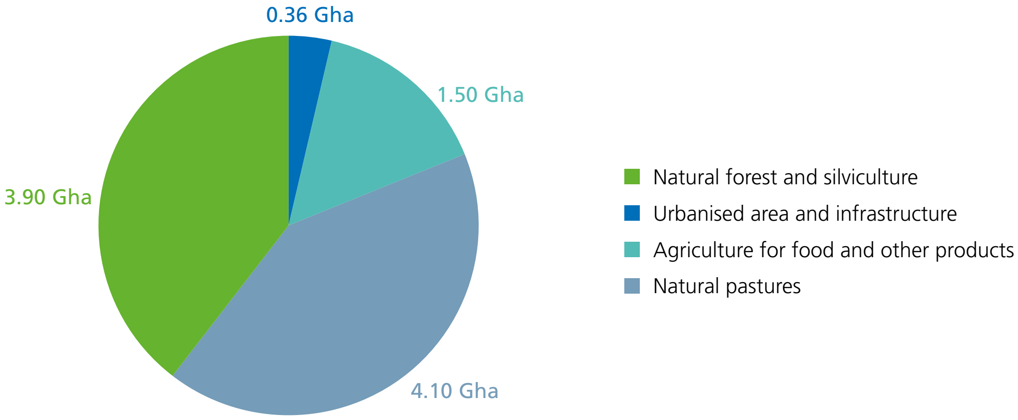
Source: FAO (2006).

In addition to the basic requirements for photosynthesis previously explored (light, water, and carbon dioxide), soil fertility and topography constitute other important factors for bioenergy production. The main mineral nutrients for plant growth are nitrogen, phosphorus, and potassium but the availability (in lower levels) of other minerals, such as boron, manganese, and sulfur, is also decisive, as is the presence of organic matter. Moreover, fertile soil shows adequate structure and porosity.

In general, bioenergy crops require the regular use of organic and chemical fertilisers to achieve satisfactory levels of productivity, and their maintenance also depends on correct soil management, including the adoption of sustainable agriculture management practices and mechanization. Regarding topography, the cultivation of lands with a high degree of slope should be avoided to reduce the incidence of erosive processes (especially in annual cycle crops) and to facilitate mechanization in soil preparation and harvesting operations.

The joint assessment of all these factors delimits potentially cultivable areas for bioenergy and all other uses. Considering the entire planet—the total dry area of which is estimated at 14.86 Gha (gigahectares or billions of hectares or even tens of millions of square kilometres)—and discounting the area glaciers and deserts occupy, the remaining terrestrial area totals 9.86 Gha, covered by urbanized areas; logistical and energy infrastructure (3.7%); areas cultivated for food, fibre, and other agricultural products (15.2%); natural pastures (41.6%); and natural and cultivated forest formations (39.6%), as shown in Figure 3 (UNEP, 2013).

FIGURE 3. Uses of cultivable surface on Earth



Source: Adapted from UNEP (2013).

As the area currently dedicated to traditional or modern bioenergy production totals less than 60 million hectares—which could require another 50 to 200 million hectares depending on the adopted technology to achieve a total bioenergy production from 100 to 200 EJ/year (SCOPE, 2015)—the demand for areas to produce bioenergy in a volume relevant to global energy consumption can be considered acceptable.

In fact, the existing availability of land for expanding agricultural frontiers, including the eventual production of bioenergy, is high, although unevenly distributed across the regions of the planet, especially in places that are still little explored or used extensively, such as low-productivity pastures. In this context, for instance, the highest potential demand estimates for bioenergy areas, 260 million hectares, represent 6% of the land currently occupied by pastures. This topic is important and will be analysed in greater detail in Chapter 8: *Global perspectives on bioethanol.*

1.4. Bioenergy technological routes

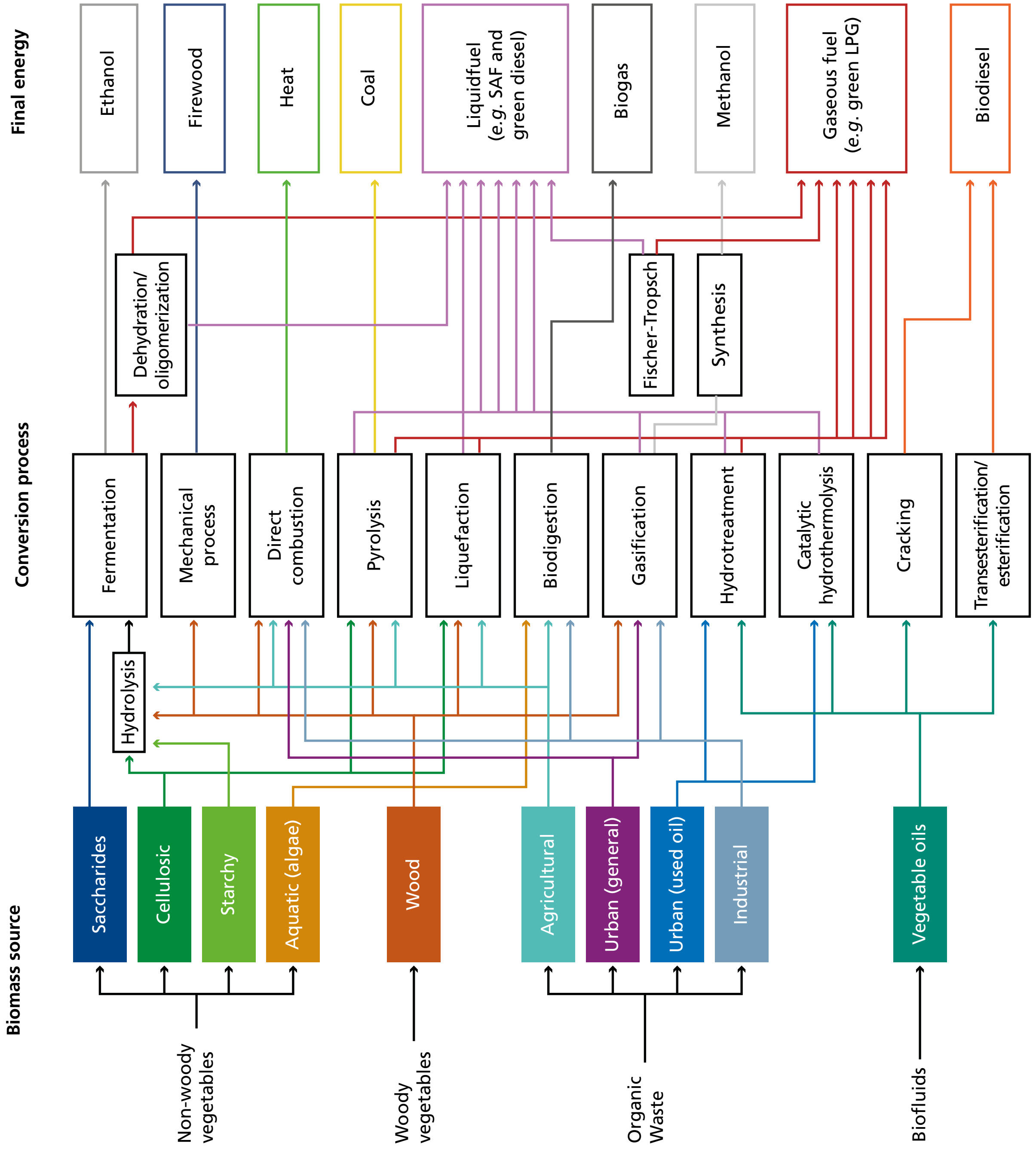
Depending on the plant, solar energy is fixed in different substances and accumulation organs, with their own physical and chemical characteristics, which, when associated with the desired final energy forms, such as vehicle fuel, fuel for furnaces and boilers, or even electricity, determine the technology adopted for its conversion. Except for some types of biomass, such as firewood and woody waste, which can be directly applied to combustion systems, biomass generally shows high humidity and inadequate particle size, density, and energy content (*e.g.*, calorific value), requiring pre-treatment before being processed for bioenergy production.

For example, the energy reserves in sugarcane, such as sucrose and bagasse, are located mainly in the stalks and are traditionally used to produce bioethanol and sugar, but they also occur in the tips and leaves of the plant, and have been increasingly used due to the wide adoption of the mechanised harvesting of green sugarcane (without pre-harvest burning), incorporating bagasse into use, expanding the availability of lignocellulosic biomass as fuel to generate process steam and electricity in plants, and reinforcing the possibilities for new applications.

In turn, the energy content in trees and other woody species is mainly stored in their trunk and branches as cellulose and lignin, basically consisting of firewood. The roots and tubers of plants such as cassava and beet accumulate starch and sucrose, whereas fruits and seeds, such as palm oil and maize, generally accumulate starch, sugar, and vegetable oils, depending on the species.

In addition to defining the most appropriate pathway to convert biomass into biofuels, global efficiency of capturing and using solar energy must consider that carbohydrate synthesis (such as cellulose and sucrose), requires around 60% less energy than fat or lipid synthesis in vegetables (Demeyer *et al.*, 1985) per unit mass of final product, which, in principle, makes the biodiesel routes comparatively less efficient than bioethanol routes, which are based on sucrose or cellulose.

FIGURE 4. Technological routes for bioenergy production



Source: Prepared by the Department of Biofuels of the Ministry of Mines and Energy, Brazil.

Figure 4 summarises several conversion pathways that can transform biomass into biofuels and useful heat. In addition to physical (purely mechanical) processes for concentration, particle size reduction, densification, or reduction of biomass moisture, two groups of chemical technologies can change the composition of raw material to provide products more compatible with end uses: **thermochemical processes**, which use raw materials with low humidity and high temperatures, and **biochemical processes**, which operate in environments with high water content and temperatures close to ambient conditions.

1.5. Evolution and perspectives of bioenergy

Bioenergy, in its different forms, was the main and, in some situations, the only form of exogenous energy supply humankind used throughout its history. Since the primitive fires dating back to over than 500,000 years ago, woody biomass has constituted the energy source par excellence, meeting domestic energy needs for cooking and heating and supplying primitive lighting systems, which used vegetable and animal fats in lamps and candles.

Subsequently and for millennia, ceramic and metallurgical production created a significant demand for bioenergy, consumed in furnaces and forges. Only from the 18th century onward did the exhaustion of firewood reserves available in much of Western Europe, and especially in England, become a determining factor in the beginning of the exploration of mineral coal, which, together with the steam engine, became one of the triggers of the Industrial Revolution. If fossil energy had not been introduced in the form of mineral coal available in abundant quantities and with relatively easy access at the time, modern history would certainly have taken a different path.

We have an interesting record from colonial Brazil of an economically relevant agro-industrial process supplied by biomass energy. As Antonil (1982) reports, during the 17th century, the sugar mills in Recôncavo Baiano had

> *[...] furnaces, which burn day and night for seven months, requiring a lot of firewood... (because) the food of fire is firewood, and only Brazil, due to the immensity*

> *of its forests, could have enough of it as it has had for so many years and which will be plentiful in the times to come, with as many furnaces as there are in the mills of Bahia, Pernambuco, and Rio de Janeiro [...].* (Antonil, 1982, p.78, our translation)

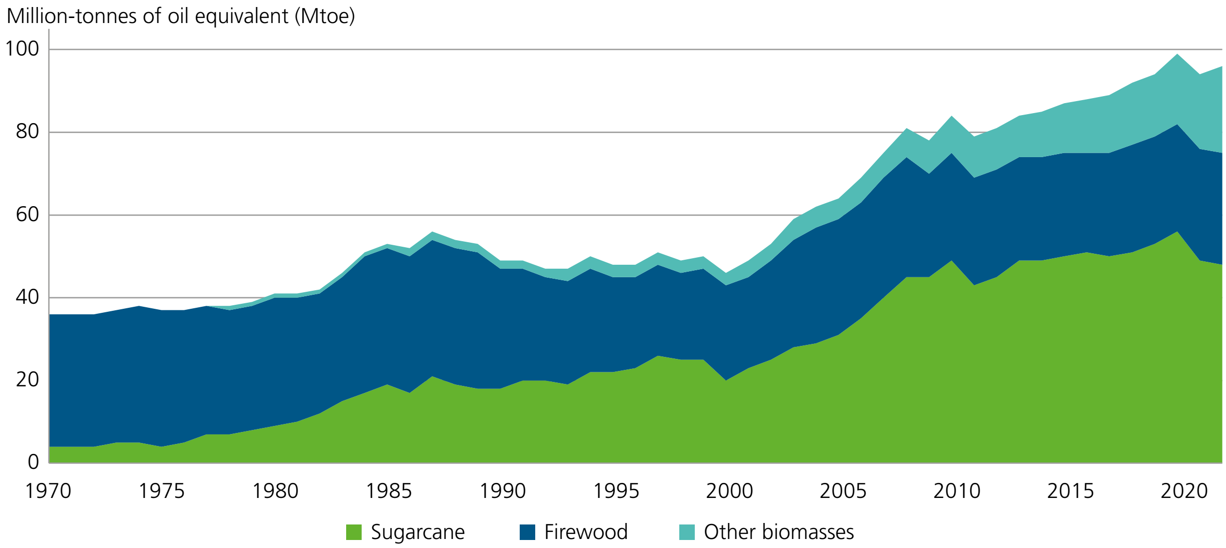
It is curious to imagine what these mills did with the sugarcane bagasse, as this by-product could serve as the primary source of energy for the production process, as is currently the case in sugar and bioethanol plants, which do not require firewood and still produce considerable surpluses of exportable energy in the form of bagasse and electricity.

As in other developing countries in tropical regions, the abundance of bioenergy resources in Brazil explains why the country began to use fossil fuels with some relevance only after 1915 and why firewood remained more important than oil in its energy supply until 1964 (Dias Leite, 2007). In fact, on many Brazilian railways, which were almost the only way of transporting cargo over moderate distances, as well as on vessels in the Amazon, on cages on the São Francisco River, and even for the generation of electrical energy in remote systems using locomotives (sets of simple steam engines and small boilers), wood was the only fuel used up to the middle of the last century.

Over the last century, with the motorization of road transport, the introduction of petroleum derivatives, and the expansion of electrical services, while appropriate and competitive bioenergy resources were available, profound changes in the profile of energy consumption promoted an interesting energy transition. On the one hand, liquefied petroleum gas progressively replaced firewood in the kitchens of Brazilian homes while several industries began to adopt sustainable forestry practices to supply firewood for furnaces and boilers and for charcoal production. On the other hand, sugar cane began to be used to produce bioethanol as a vehicle fuel since 1931, becoming especially relevant after 1975. In recent years, ethanol has replaced around half of the gasoline consumption in Brazilian cars and motorcycles and has contributed to the supply of electrical energy, with cogeneration systems in sugar and alcohol plants reaching 6.2% of total generation in the country in 2020 (EPE, 2023b).

Graph 2, which organises the dynamics discussed in the previous paragraph, shows how bioenergy consumption has evolved in Brazil in recent decades, identifying the portions attributable to sugarcane, firewood, and other forms of biomass. The latter mainly includes cellulosic bleach, an important biofuel in plants producing cellulose and other co-products from processing of agricultural raw materials used as a source of energy in industries. In 2023, sugarcane, firewood, and other forms of bioenergy consumed in the Brazilian socioeconomic sectors corresponded, respectively, to 16.8%, 8.6%, and 7.2% of the primary energy production in the country, totalling 102.6 Mtoe (million tonnes of oil equivalent), i.e., 33% of the total energy supply and 67% of the renewable energy production that year, making it the most important renewable source in the energy matrix (EPE, 2024a).

GRAPH 2. Bioenergy production by source in Brazil

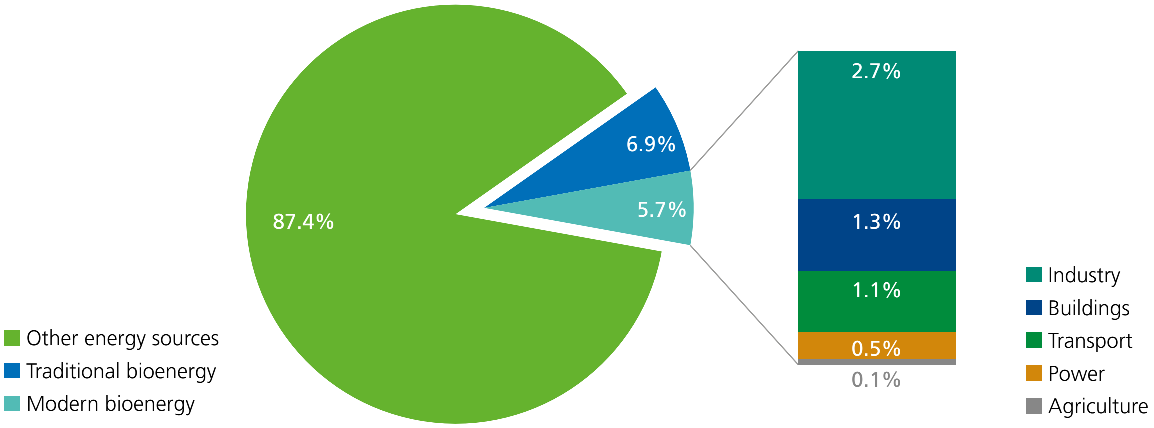


Source: Prepared by the authors based on EPE (2024a).

In global terms, despite the notable expansion of other forms of renewable energy in recent times, bioenergy remains the most important renewable energy source, capable of providing heat by direct combustion, electricity, and fuels for transportation. In 2020 the final consumption of bioenergy was estimated at 45.6 EJ, representing 12.6% of the global energy consumption. Modern uses of bioenergy in industry, buildings, transport, and agriculture accounted for 20.6 EJ, constituting 5.7% of the total energy consumption, as indicated in Graph 3 (REN21, 2024).

According to the International Energy Agency (IEA), although the use of bioenergy has grown by an average of 3.3% per year from 2010 to 2022, considering the need to decarbonise global energy systems, it is expected to grow more rapidly in the coming years (IEA, 2023b). According to a 2020 global assessment by the International Renewable Energy Agency (IRENA), the contribution of modern bioenergy from efficient sustainable processes, totalled 11% in industries, 5% in buildings, 7.4% in agriculture, 3.6% in transportation, and 2.3% in electricity generation, indicating both advances and opportunities for expansion (IRENA, 2023).

GRAPH 3. Global bioenergy consumption



Source: Prepared by the authors based on REN21 (2024).

This brief review of the development and current state of bioenergy production and use systems in Brazil and around the world allows us to observe that bioenergy systems present a marked dichotomy between two large and differentiated paradigms and that they are experiencing a transition.

The first case includes traditional systems, practiced for thousands of years, in which biomass resources are extracted without economic valuation of biofuels and generally by systems of low efficiency and productivity, meeting the needs of homes and small traditional industries. Examples of this situation include the use of firewood for domestic cooking in rural areas, a common practice that significantly impacts users' health. A second paradigm refers to modern bioenergy systems, in which production almost always occurs on a commercial basis by sustainably producing bioenergy feedstocks and efficiently converting into modern energy vectors to meet the energy needs of modern industry, the transportation sector, and electricity generation.

The global evolution of bioenergy increasingly points to a reduction in the contribution of traditional bioenergy, with its use shifting to less impactful applications, such as small rural industries, while modern bioenergy grows, replacing fossil energy sources. Thus, bioenergy is progressively no longer considered an “old” energy, but is currently recognised as a modern, competitive, and adequate form of energy that can provide real advances toward rationality and sustainability.

2.

Bioethanol as a fuel for mobility

All the world is waiting for a substitute for gasoline.
The day is not far distant when,
for every one of those barrels of gasoline,
a barrel of alcohol must be substituted.

Henry Ford,
in an interview with The Detroit News, 1916.

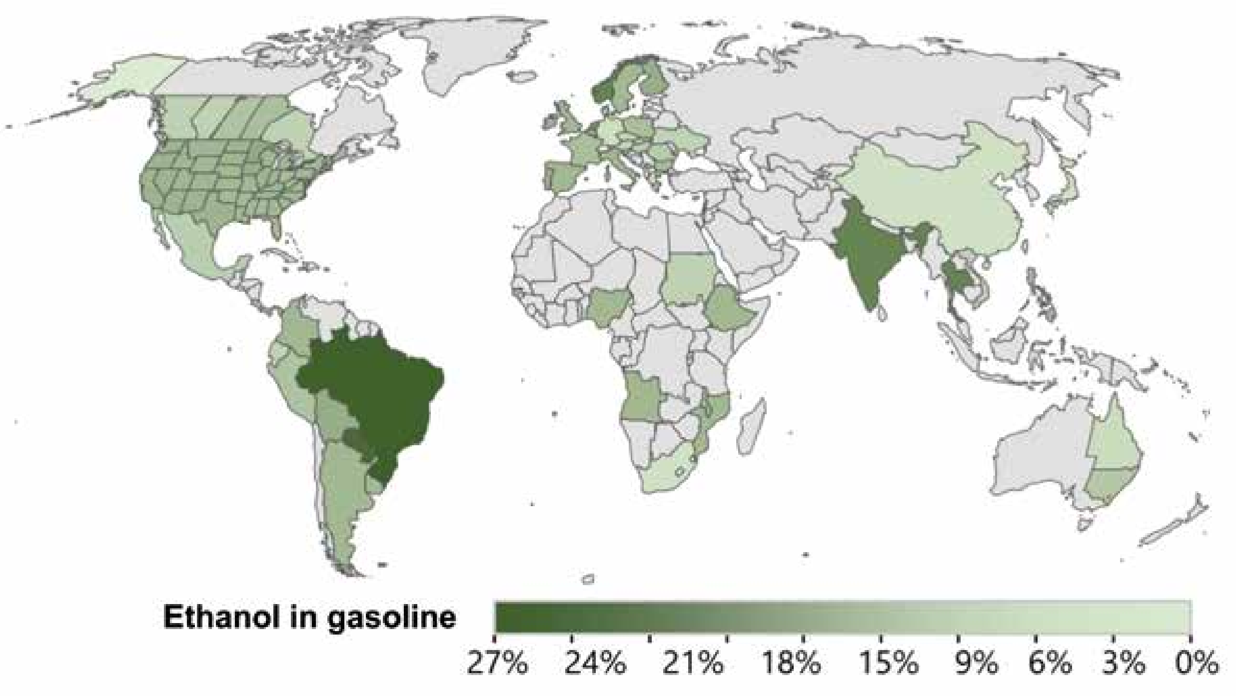
This chapter is largely based on drafts prepared for this book by Ricardo Abreu, an automotive industry consultant, along with contributions from Marlon Arraes Jardim Leal, José Nilton de Souza Vieira, and Lorena Mendes de Souza from the Brazilian Ministry of Mines and Energy.

Ethyl alcohol, also called bioethanol when produced from vegetable raw materials, originated with the development of the distillation process by Arab alchemists during the Middle Ages. Since then, bioethanol has been used for a variety of purposes, including as a household fuel for lighting, heating, and cooking. In 1860, Nicolaus Otto, the inventor of the spark-ignition internal combustion engine, used bioethanol in one of his engines (EIA, 2008). The automotive use of this biofuel had its first expansion phase at the beginning of the last century, later giving way to gasoline until its recent revival due to its economic, environmental, and strategic advantages.

Energy used for transportation, 95% of which is based on oil and natural gas, currently accounts for around 30% of global energy consumption. As a result, emissions in this sector account for a third of atmospheric fossil carbon emissions (IEA, 2023a). When compared to other energy-consuming sectors, transport is the most resistant to decarbonization, which has been justified by the limited flexibility of vehicle fleets to adopt more sustainable technologies and the need for high investments in production and distribution infrastructure and in the use of new energy technologies.

However, bioethanol is a versatile fuel, as befits the mobility of the future. It is among the few renewable fuels capable of being used efficiently in thermal machines such as combustion engines and turbines, as well as being suitable for electrochemical devices such as fuel cell. Bioethanol can also be adopted in the short term by the current global fleet of cars and motorcycles, in blends with gasoline ranging from 1% to 30%, as has been happening in dozens of countries, as shown in Figure 5. Several countries also have fleets of “flex” vehicles, which can be fuelled with pure bioethanol (E100), such as Brazil, Paraguay, and India, or with high percentages of bioethanol (E85), such as Canada, the United States, and Europe.

FIGURE 5. Countries that use bioethanol fuel blended with gasoline; Brazil and Paraguay also use pure bioethanol



Source: Cantarella *et al*. (2023).

This chapter first presents the secular history of the use of bioethanol in vehicles. Next, its physical and chemical characteristics of interest are explored and its performance in modern propulsion engines is evaluated, compared with other energy carriers currently adopted or proposed, including electricity in various designs, suggesting possible paths for its progressive and immediate adoption. A reference in this regard is the Brazilian experience, encompassing the consolidated use of flexible vehicles, which use any blend of bioethanol, and the mandatory 27% blend of bioethanol with gasoline—recently increased to 30%—, both established for almost a decade, along with the widespread use of pure hydrous ethanol as a fuel in alternative engines for agricultural aircraft. In conclusion, emerging technologies for the use of bioethanol in vehicles with diesel engines and fuel cells are presented.

2.1. Brief history of bioethanol as an automotive fuel

As a pioneer, in 1896 Henry Ford demonstrated the use of pure bioethanol in his first automobile and, from 1908 onwards, regularly produced the Ford Model T capable of using it (EIA, 2008). At the beginning of the automobile age, this biofuel was widely used in internal combustion engines, either mixed with gasoline or pure.

FIGURE 6. Henry Ford with a Model T Ford using pure ethanol as a fuel

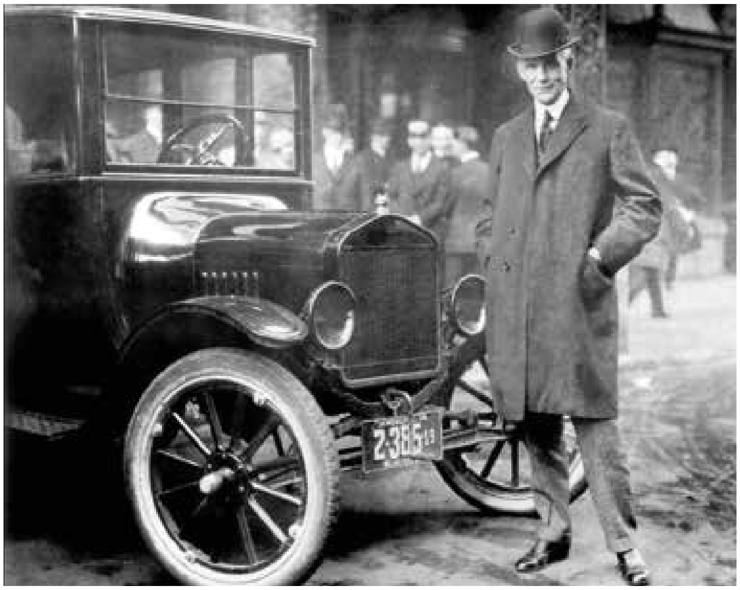


Photo: Ford Motor Company/Wikimedia Commons/Public Domain. Available at: https://commons.wikimedia.org/ wiki/File:H.Ford_et_sa_Ford_T.jpg. Accessed on: Sep. 2024.

In addition to the United States, countries such as South Africa, Germany, Angola, Argentina, Australia, Austria, Brazil, Chile, China, Cuba, the Philippines, France, India, Italy, Japan, Malaysia, Poland, the United Kingdom, Switzerland, and Vietnam have adopted bioethanol fuel, either mandatorily or as an alternative, to address gasoline shortages. These government measures reflected recognition of its renewable nature and its potential for local production, especially in countries that depended on imported fuels and already produced bioethanol (Kovarik, 2006). At this time, especially in Europe, congresses were held to explore and disseminate the use of this biofuel, featuring exhibitions of stoves, heaters, coffee roasters, lamps, and engines, manufactured mainly in Germany (Automobile-Club de France, 1903).

However, in the early decades of the last century, interest in bioethanol fuel waned, with a few exceptions, such as Brazil, which has maintained the mandatory use of bioethanol in gasoline since 1931, as presented in Chapter 5. In the United Kingdom, for example, National Distillers continued to market a blend of ethanol and gasoline until 1968, when the company's fuels and chemicals division was bought by British Petroleum (Kovaric, 2006). The main disincentive to the use of bioethanol fuel was the growth of the oil industry, which increased the supply of gasoline at low prices. In addition, in the United States, where the main car manufacturers were at the time, the Prohibition banned the production and sale of ethanol from 1920 to 1933.

In the 1970s, the Brazilian National Alcohol Programme (Proálcool) was implemented by the Brazilian government as a strategic response to the 1973 oil crisis, encouraging the production of ethanol from sugar cane. The programme was a pioneering measure aimed at replacing gasoline with ethanol on a large scale, taking advantage of Brazil's abundant land and agricultural tradition. This initiative not only contributed to reducing oil imports and adjusting the balance of payments, but also fostered the modernization of the sugar-alcohol sector and the technological development of the Brazilian automotive industry via the development of engines powered exclusively by hydrous ethanol (E100), as will be described in Chapter 5: *Evolution of bioethanol production and use in Brazil.*

It was in the 1990s, with greater awareness of the impacts of fuel emissions on the local and global environment and the worsening climate crisis, that the use of bioethanol as a fuel entered a new global era. In addition to reducing dependence on fossil fuels purely for geopolitical or economic reasons, environmental and sustainability reasons have been considered, requiring the reduction of greenhouse gas emissions and air pollutants, with all countries participating in this effort.

Despite bioethanol's long history of regular and successful use in many countries on all continents, in some countries doubts and questions remain about its performance and emissions. These issues are addressed in the following topics, which reflect international advances and trends, the long and rich experience with bioethanol in combustion engines, and Brazil's significant automotive production using this biofuel.

2.2. Characteristics of ethanol as a fuel

Ethanol, bioethanol or of petrochemical origin, offers advantages over conventional petroleum-based fuels due to its chemical composition. Its primary advantage is its high oxygen content, which makes up around 35% by mass of ethanol, which increases its resistance to detonation, also known as its octane rating. A higher octane rating enables better use of the energy released in combustion and is one of the most important properties of a fuel for Otto cycle engines.

There are two standardised methods for measuring the octane rating of fuels: the RON method, in which the engine operates under relatively mild conditions, and the MON method, in which it operates under severe conditions. Table 3 shows the main properties for a typical gasoline, which can vary slightly because it is a mixture of hundreds of different hydrocarbons, usually represented by octane (C_8H_{18}), and for ethanol, whose properties are more stable because it is a simple substance, C_2H_6O.

TABLE 3. Physical and chemical properties of gasoline and bioethanol

PARAMETER	UNIT	GASOLINE	ETHANOL
Lower calorific value	kJ/kg	43,500	28,225
	kJ/litre	32,180	22,350
Density	kg/litre	0.72 – 0.78	0792
Octane rating RON (research octane number)	-	90 – 100	102 – 130
Octane rating MON (motor octane number)	-	80 – 92	89 – 96
Latent heat of vaporization	kJ/kg	330 – 400	842 – 930
Stoichiometric air/fuel ratio	-	14.5	9.0
Vapour pressure	kPa	40 – 65	15 – 17
Ignition temperature	°C	220	420
Solubility in water	% in volume	~ 0	100

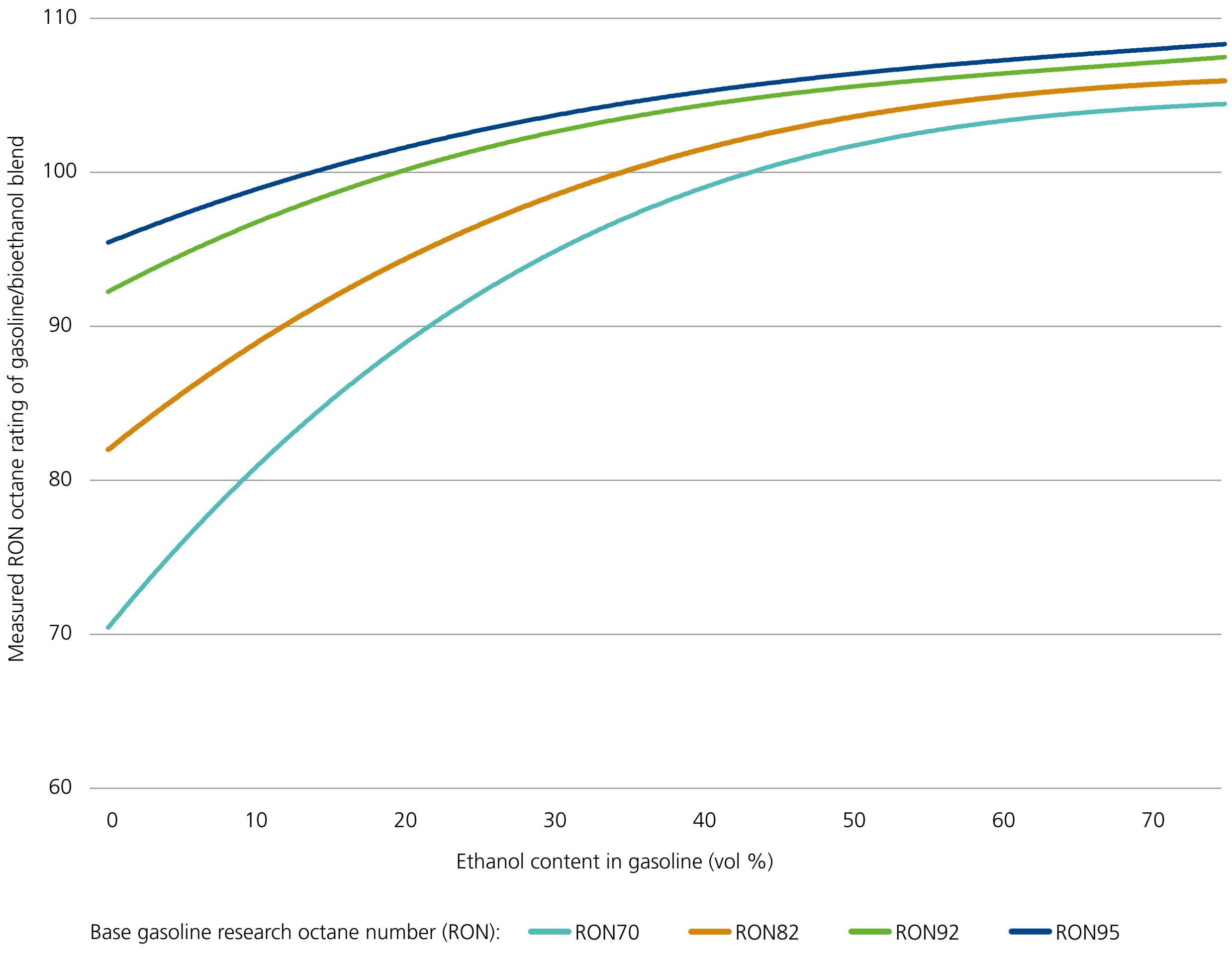
Source: Prepared by the authors based on API (1998) and Goldemberg and Macedo (1994).

2.2.1. Ethanol's effect on octane rating

Pure gasoline, as produced in oil refineries, always needs its properties adjusted to a specification that ensures satisfactory performance, greater engine efficiency, and limited pollutant emissions. In this sense, when mixed with gasoline, ethanol behaves as an additive, an octane booster, increasing the RON and MON values to levels meeting or exceeding the standard and, due to its oxygen content, reducing emissions of polluting gases. As implemented in several countries, ethanol added to gasoline has replaced the high-priced carcinogenic hydrocarbons previously used as octane booster additives.

Ethanol blending enables the use of lower octane, cheaper base gasolines, known in the fuel market as reformulated blendstock for oxygenate blending (RBOB), which, as shown in Graph 4, can have a lower octane rating, starting at RON 70. It is estimated that for every three percentage points of anhydrous ethanol blended into gasoline, there is an increase of one octane rating point (RON). In other words, higher ethanol blends make it possible to use lower quality gasoline.

GRAPH 4. Effect of ethanol addition on the RON octane rating of gasoline



Source: Prepared by the authors based on Wang *et al*. (2017).

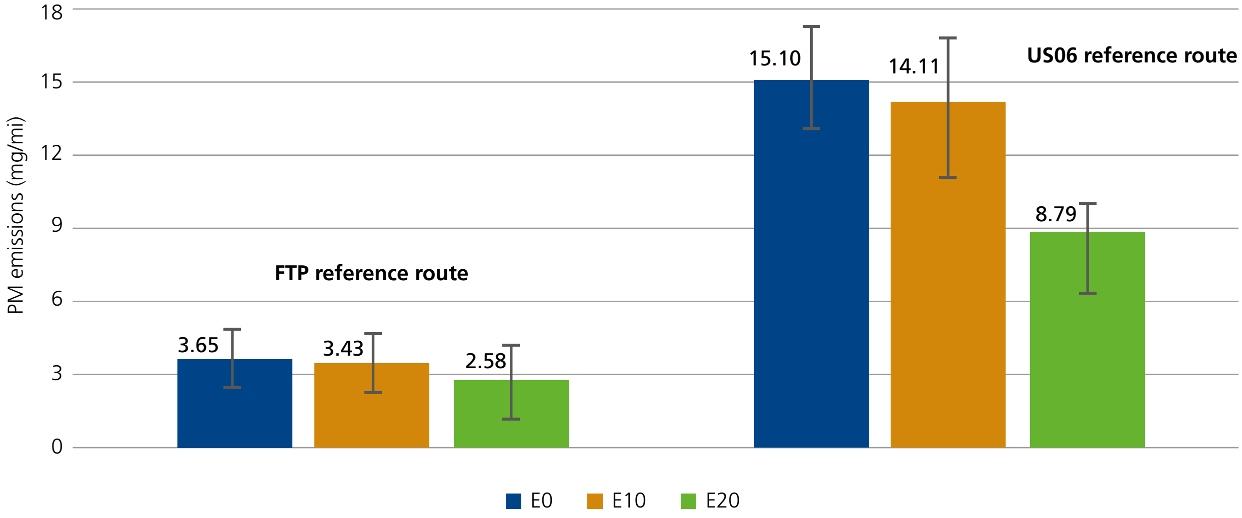
Currently, more than 60 countries use varying percentages of anhydrous ethanol in gasoline, from 5% to 27%, with 10% ethanol (E10) as the most widely used blend. Seeking to harmonise fuels globally, the Worldwide Fuel Charter (WWFC), an initiative promoted by major global motor vehicle manufacturers' associations, including the European Automobile Manufacturers Association, the US Alliance of Automobile Manufacturers, and the Japan Automobile Manufacturers Association, expressly accepts the use of gasoline with 10% ethanol for all gasoline engines (ACEA, 2019). The WWFC also presents a specification for ethanol to be blended with gasoline (OICA, 2009). In Brazil, the specifications for anhydrous and hydrous ethanol are established and periodically revised by the Brazilian National Agency for Petroleum, Natural Gas and Biofuels (ANP, 2015).

The WWFC recommends blending up to 20% ethanol with gasoline, with the vehicle manufacturer's consent, in modern engines prepared to use high octane fuel (HOF), with a RON above 97, which is becoming a strong trend in future gasoline specifications.

2.2.2. Ethanol's effect on local emissions

Another important characteristic of ethanol is its ability to reduce exhaust emissions, particularly particulate matter. This type of emission has become a major environmental concern with the spread of gasoline engines with direct injection. As indicated in Graph 5, depending on the engine's calibration, higher blends of ethanol can eliminate the need for a particulate filter, as a 30% to 40% reduction in particulate emissions can be achieved with E20. In addition, the use of ethanol in supercharged engines with direct fuel injection leads to a significant reduction in emissions of polycyclic aromatic hydrocarbons (PAH), which are potentially carcinogenic and have not yet been controlled. Tests with E10 and E85 have shown reductions of 77% and 84% respectively in these compounds.

GRAPH 5. Effect of adding ethanol on particulate material emissions, evaluated for two reference routes (FTP and US06)



Source: Prepared by the authors based on AMF (2019).

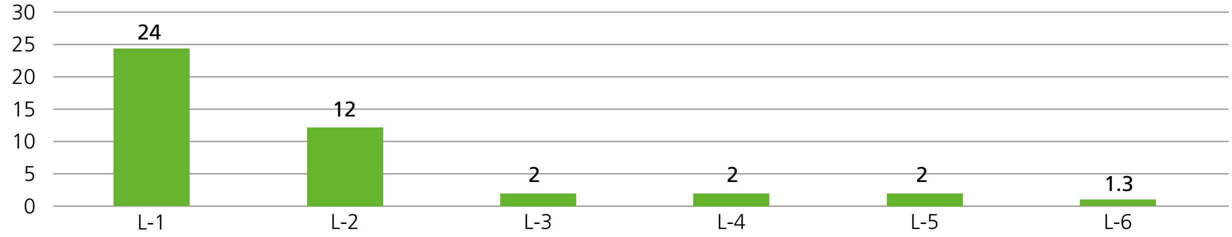
When it comes to local impact caused by vehicle emissions, it is necessary to consider emissions of nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC), non-methane organic gases (NMOGs), which include aldehydes (RCHO), and particulate material (PM) from engines operating under conditions representative of vehicle use (reference routes), as well as their environmental interactions throughout their complete life cycle, similar to the approach for greenhouse gases (Branco *et al.* 2022).

In general, engines burning pure ethanol or blended with gasoline comply with vehicle emissions legislation, such as Brazil's Programme for the Control of Air Pollution from Motor Vehicles (PROCONVE). Since 1988 and with periodic revisions (the sixth phase, L6, has been in force since 2014), this programme establishes limits for motor vehicle emissions in Brazil, shown in Graph 6, aligned with limits adopted in other countries and mandatorily met by vehicles produced in Brazil or imported, using fuel with at least 27% ethanol.

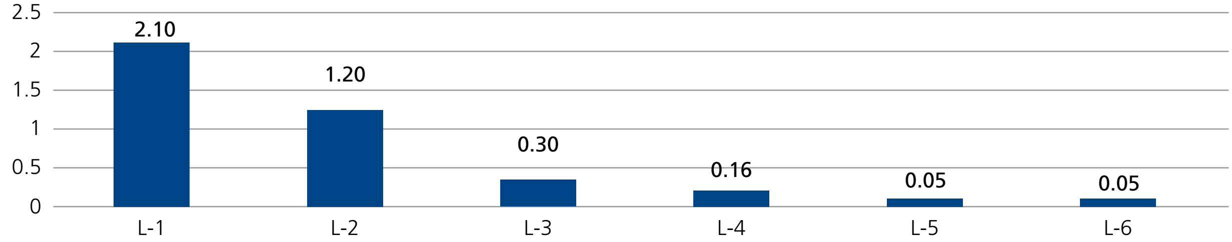
One group of pollutants particularly associated with the burning of ethanol in engines is aldehydes (acetaldehyde and formaldehyde), which are emitted mainly in the early stages of the vehicle's driving cycle, when the engines are relatively cold. In this sense, the establishment of strict limits on the emission of NMOGs and aldehydes from engines was important and well received by the automotive industry. It is worth noting that aldehyde emissions from ethanol combustion are mainly formed by acetaldehyde, a type of aldehyde that is less aggressive and better tolerated than formaldehyde, a toxic and carcinogenic compound (Souza *et al.*, 2013).

GRAPH 6. Evolution of pollutant emission limits for new light vehicles in Brazil, required under PROCONVE phases L1 to L6 from 1988 to 2022

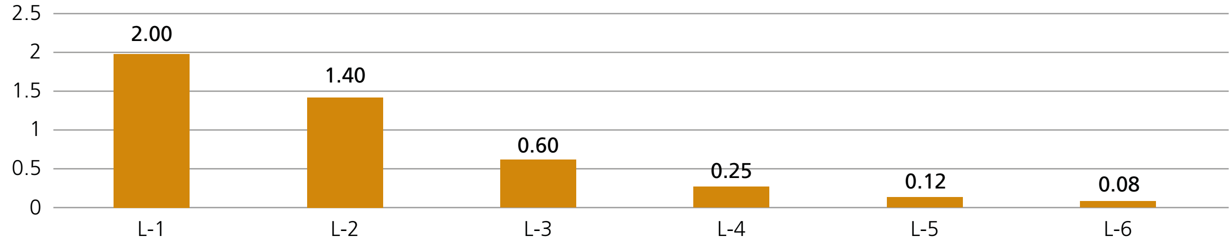
GRAPH 6A. Carbon monoxide – CO (g/km)



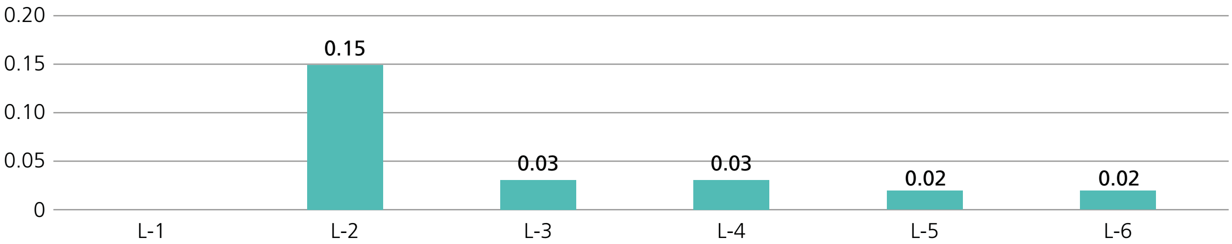
GRAPH 6B. Hydrocarbon – HC (g/km)



GRAPH 6C. Nitrogen oxides – NO_x (g/km)



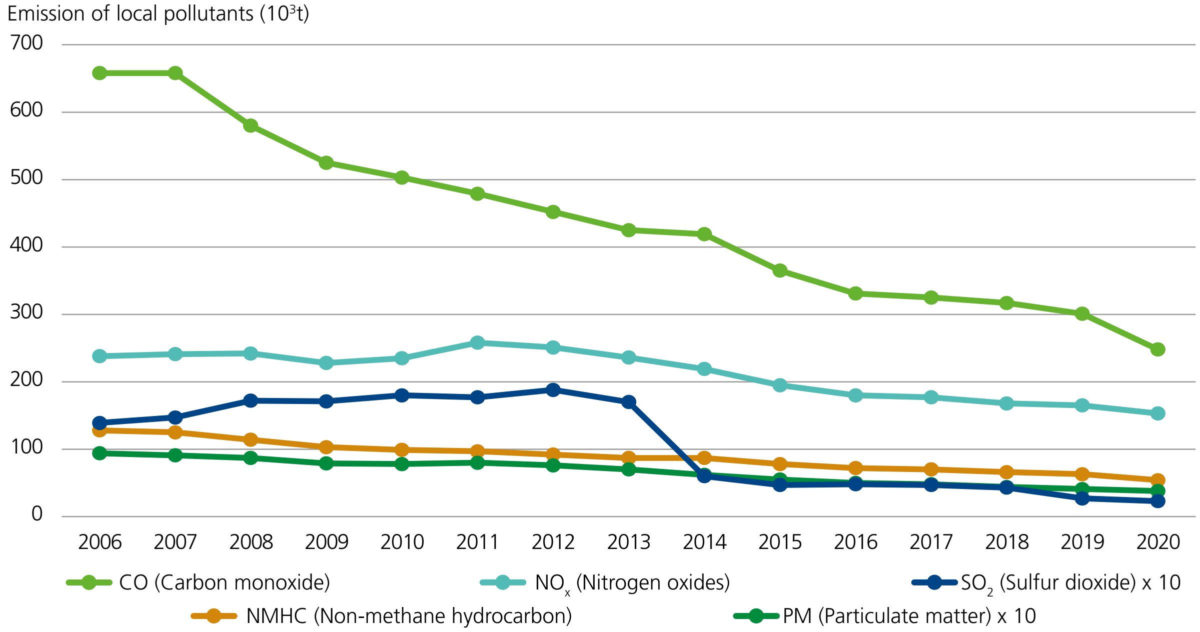
GRAPH 6D. Total aldehydes – CHO (g/km)



Source: IBAMA (2024).

A good example of the environmental benefits of using ethanol and adopting emission limits can be seen in São Paulo State, which accounts for around 30% of the Brazilian vehicle fleet. Even with the significant and growing consumption of pure ethanol and ethanol mixed with gasoline, and the constant expansion of the fleet, which increased from 15 million to almost 31 million motor vehicles between 2006 and 2019, pollutant emissions from motor vehicles in this period showed some improvement, as shown in Graph 7 (CETESB, 2022). Epidemiological studies on the impact of the use of fuel ethanol on public health in Brazilian metropolitan regions have indicated an improvement in the life expectancy and quality of life of the population in these regions, while also contributing to the reduction of public spending on health (EPE, 2021).

GRAPH 7. Evolution of vehicle pollutant emissions in São Paulo State



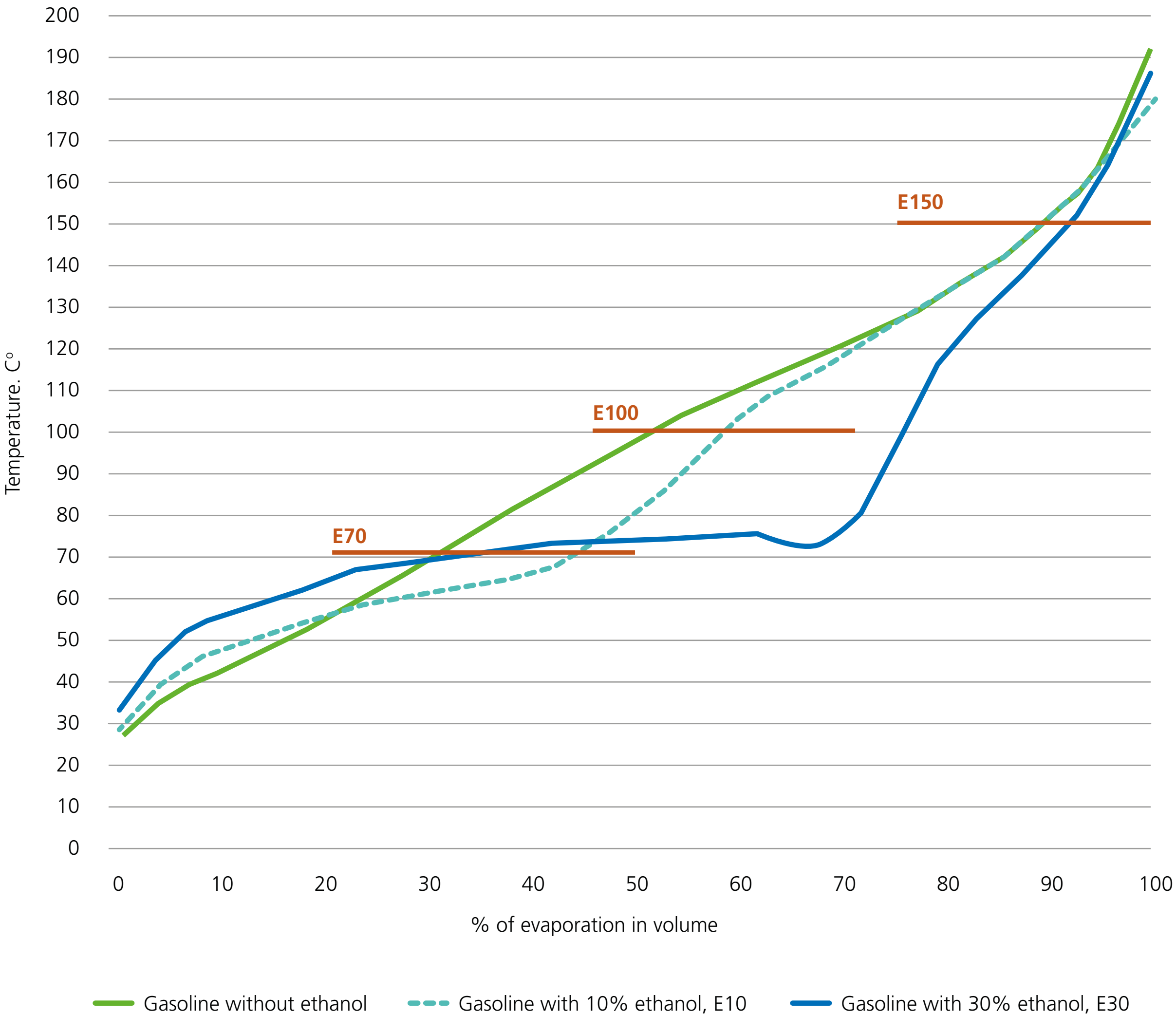
Source: CETESB (2022).

2.2.3. Effect of fuel volatility on driveability

For a fuel to burn properly, it needs to be well mixed with air. Therefore, the ease with which a liquid fuel vaporises is an important property that directly impacts various aspects of vehicle performance, such as cold or hot starting conditions, acceleration, fuel economy, and lubricating oil dilution. Precisely for this reason, petroleum-based fuels must have a balanced composition of light and heavy fractions, producing a distillation curve in which the product begins to vaporise at relatively low temperatures and finishes at temperatures much higher than room temperature.

The addition of ethanol tends to lower the distillation curve (AMF, 2019), especially in its first half, impacting the so-called T50 temperature, corresponding to 50% of the evaporated mass, although the initial and final distillation temperatures are little affected, as shown in Graph 8. In this graph and in the comments that follow, pure gasoline refers to the product meeting the usual quality specifications, without ethanol blending.

GRAPH 8. Effect of ethanol addition on the gasoline distillation curve



Source: Prepared by the authors based on AMF (2019).

In Graph 8, with the distillation curves for pure gasoline, E10, and E30 (from a typical base gasoline), the red lines show the horizontal limits of percentage evaporated at 70°C, 100°C, and 150°C, which are specification ranges according to the European Standards for Gasoline (EN228). In the case of adding 30% ethanol, the fraction evaporated at 100°C exceeds the upper limit, which can be compensated by adjusting the hydrocarbons in the base gasoline, used for ethanol additives, as mentioned above.

In fact, current gasoline vehicles operate efficiently on gasoline-ethanol blends, provided that the necessary fuel specification adjustments are made to ensure compliance with established quality standards. This technical adjustment is essential to avoid performance losses and driveability issues.

Gasoline containing 10% ethanol requires 16.5% more heat to vaporise completely than gasoline without ethanol. This could make it difficult to start the engine at very low temperatures. However, the US case shows that there is no such problem. The country has a mandate to use this blend all year round, and the engines of two and four-wheeled vehicles exhibit no driveability issues in the cold phase of engine use. In addition, the use of heating devices at start-up and direct injection has greatly mitigated this problem, which could exist at higher blend levels.

On the other hand, the higher heat of vaporization of ethanol-blended gasoline is one of the main reasons why the efficiency of an engine using this fuel increases from 1% to 2% compared to pure gasoline. Ethanol contributes to the cooling of the combustion chamber, enabling higher compression ratios with lower emissions of nitrogen oxides (NO_X). Thus, even if gasoline with 10% ethanol contains 3.3% less energy per volume unit, the final effect on fuel consumption is smaller and depends on the conditions of use (Orbital, 2002). This point is relevant: at levels of up to 10%, the effect of adding bioethanol on vehicle consumption is less than the variation in consumption observed between different drivers and, for practical purposes, a litre of ethanol-blended gasoline produces virtually the same effects as a litre of pure gasoline (Salih & Andrews, 1992; Brusstar & Bakenhus, 2005).

On the other hand, for higher levels of ethanol, such as 25% in premium gasoline or 27% in regular gasoline (30% from August 2025), which are currently used in Brazil and correspond to a lower energy content by volume, the average increase in consumption is lower than expected due to the difference in energy content between these blends and pure gasoline.

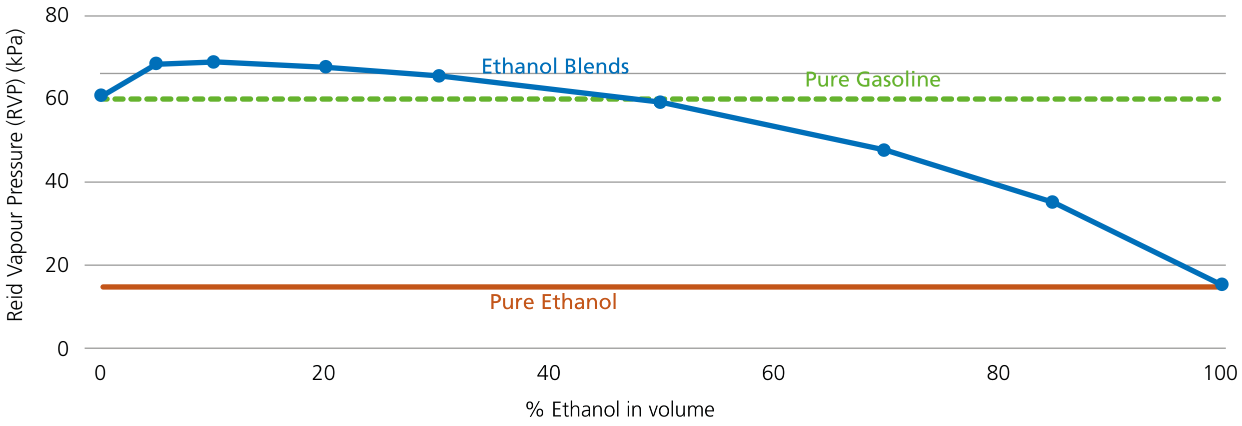
These results, which have been confirmed in many field tests, show that although ethanol has a lower calorific value, it improves engine efficiency and power due to the lower intake temperature and the greater volume of combustion products resulting from the oxygen content in ethanol.

2.2.4. Ethanol's effect on partial vapour pressure

A property related to volatility—vapour pressure—is significantly impacted by the addition of ethanol. Vapour pressure determines the level of evaporative emissions and the likelihood of vapour formation in the fuel supply lines, an issue that has been eliminated by the current use of in-tank fuel pumps, standard in vehicles since the end of the last century.

Notably, although the vapour pressure of pure gasoline is higher than that of pure ethanol, the addition of ethanol to gasoline raises the vapour pressure of the blend, as shown in Graph 9. This increase typically peaks at around 5% ethanol by volume in gasoline, then gradually decreases as the ethanol content rises. For example, a given gasoline composition receiving 5% ethanol has its vapour pressure raised to 7 kPa, whereas at 10% by volume, the pressure drops to 6.5 kPa (Furey, 1985). As observed for the distillation curve, this effect can be corrected by adjusting the composition of the base gasoline to ensure that the blend meets the desired specifications.

GRAPH 9. Effect of ethanol on the vapour pressure of pure gasoline



Source: Furey (1985).

In fact, in countries that blend ethanol into gasoline, the vapour pressure has been specified at levels comparable to those of standard gasoline. In addition to the limits set in the fuel specification, evaporative emissions in vehicles have been controlled since the 1970s by applying activated carbon filters and associated systems, which capture and store fuel vapours from the tank until they are redirected to the engine, where they are burned during normal vehicle operation.

Similar measures, such as the use of activated charcoal filters and vapour recovery systems during refuelling, have been adopted with good results in the distribution and refuelling of ethanol and gasoline blends. In the case of pure ethanol, the four times lower vapour pressure is already a natural control of evaporative emissions throughout the operating cycle and effectively offsets the emission of more volatile compounds when vehicles are started cold.

2.2.5. Compatibility with automotive materials

Despite widespread use and endorsement by vehicle manufacturers, there is still localised resistance to adding ethanol to gasoline due to concerns about incompatibility with certain materials, especially in older vehicles. However, extensive experience in countries such as Brazil, the United States, and more recently India, has shown that this issue no longer exists. This is the key conclusion of studies analysing the use of ethanol in various countries (Abel *et al.*, 2021).

Older materials such as plastics, natural rubber, and butyl rubber—previously used in seals, tubes, and filters and prone to faster degradation more quickly in the presence of ethanol—have been replaced by fluorinated elastomers since the 1980s, solving this issue.

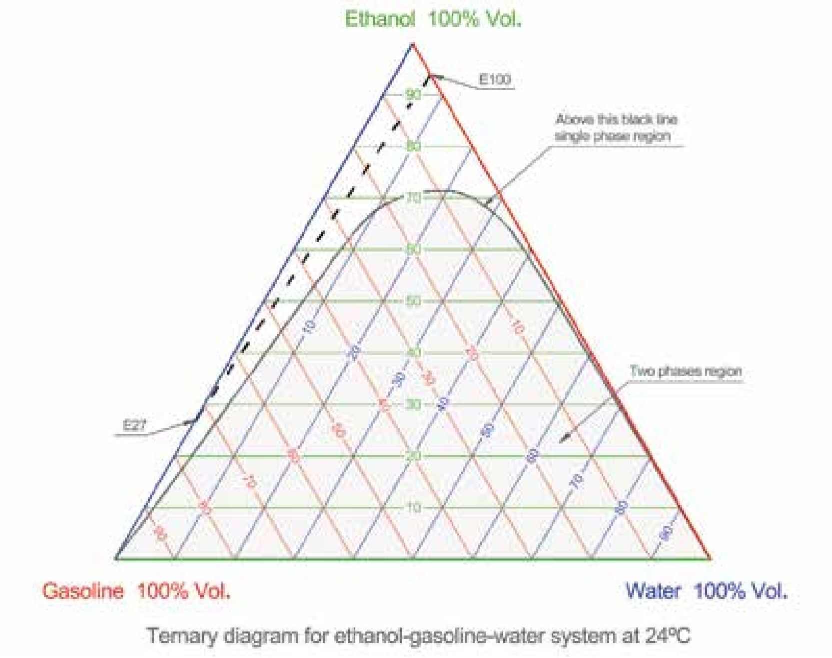
Similarly, the metal alloys and surface treatments used in ethanol-compatible components have been incorporated into all engines due to the demands of new technologies—such as high-pressure injection systems, increased combustion pressure and temperature, and, above all, the legal requirement to reduce and maintain vehicle emission levels throughout their lifespan, regardless of the fuels used.

Another important aspect is ethanol quality control, which requires compliance with technical specifications—particularly regarding maximum levels of total acidity, pH, electrical conductivity, and limits for certain ions (chlorides, sulphates, iron, sodium, and copper). For this reason, the correct definition and strict observance of the biofuel specification are essential to the success of an ethanol fuel programme.

2.2.6. Phase separation in gasoline blends

The possibility of phase separation in an ethanol-gasoline mixture is sometimes cited as a challenge for the adoption of bioethanol. There is an unfounded fear in some countries that water condensing inside a vehicle's fuel tank, or water eventually absorbed by the bioethanol, could separate from the blend, settle at the bottom of the tank, and hinder normal engine operation. Strictly speaking, there is no such risk, as clearly illustrated by the phase diagram shown in Graph 10.

GRAPH 10. Solubility of water in gasoline-ethanol blends



Source: Graph prepared by the Sugarcane Technology Centre (CTC) in 1998 and kindly provided to the authors by Leal, M.R.L.

This triangular diagram is a fundamental tool for representing ternary systems with liquid-liquid equilibrium, such as mixtures of water, gasoline, and ethanol. In this type of diagram, each vertex represents a pure component, the edges indicate binary mixtures, and the interior represents ternary mixtures. A curve within the triangle outlines the region where two immiscible liquid phases occur; outside this region, total miscibility is observed, with all components forming a single liquid phase.

Regarding water separation, it is worth considering the case of flex-fuel vehicles, which can use any blend of gasoline and hydrous ethanol, widely adopted in Brazil and discussed in the next section. In Graph 10, the dashed line represents different possible scenarios in the fuel tank of a flex-fuel vehicle. The first point corresponds to 100% E27 gasoline, which contains 27% anhydrous ethanol. The last point represents pure hydrous ethanol, with 7.5% water (by mass). The intermediate points indicate mixtures of E27 gasoline and hydrous ethanol, as commonly found in flex-fuel vehicles. All of these compositions fall outside the phase separation region, meaning they remain fully miscible. In fact, ethanol reduces the risk of phase separation because it mixes well with both water and gasoline, whereas gasoline alone does not mix with water. Even at low temperatures, the miscibility of water in ethanol-gasoline blends pose no significant issues. For example, E10 remains a stable fuel, with no phase separation down to −40°C (Christensen & McCormick, 2016).

Therefore, it can be concluded that phase separation is not a technical concern, provided that the fuels meet regulatory quality standards. Under these conditions, miscibility among the components is maintained, allowing for the reliable and efficient operation of vehicles fuelled with ethanol in blends or pure.

2.3. Pure ethanol and flexible fuel engines (flex-fuel)

Until the end of the last century, the significant difference in the air/fuel ratio between gasoline and ethanol, as shown in Table 3, meant that engines had to be manufactured or adapted specifically for use with gasoline containing higher levels of ethanol or with pure ethanol. However, in recent decades, with the development of advanced air/fuel mixture and ignition control systems, flex-fuel engines have been launched. These engines are capable of operating on gasoline, ethanol, or blends of the two in any proportion, without any driver intervention, while meeting efficiency, driveability, and legal exhaust emissions requirements (Joseph Jr., 2007).

Regarding flexible vehicles, two concepts have been adopted. In Brazil, users can choose the fuel they wish to use at the time of refuelling, depending on convenience, ranging from 100% hydrous ethanol (with 5.5% water by volume) to gasoline containing from 18% to 30% anhydrous ethanol. These fuels are available at more than 42,000 service stations across Brazil. The introduction of these vehicles, produced in various models from 2003 onwards, was well received by Brazilian consumers and has since accounted for a significant majority of new vehicle sales. This concept has also been adopted in India, where, following the mandatory implementation of a 10% ethanol blend in gasoline in 2021, the goal is to reach 20% by 2025, facilitating the introduction of these flexible vehicles (India MTRH, 2022).

In the United States, Canada, and Europe, flex-fuel vehicles operate on a range of ethanol contents, from pure gasoline, without ethanol, to a blend containing 85% anhydrous ethanol and 15% gasoline, marketed under the acronym E85, whose gasoline content allows cold starts at very low temperatures.

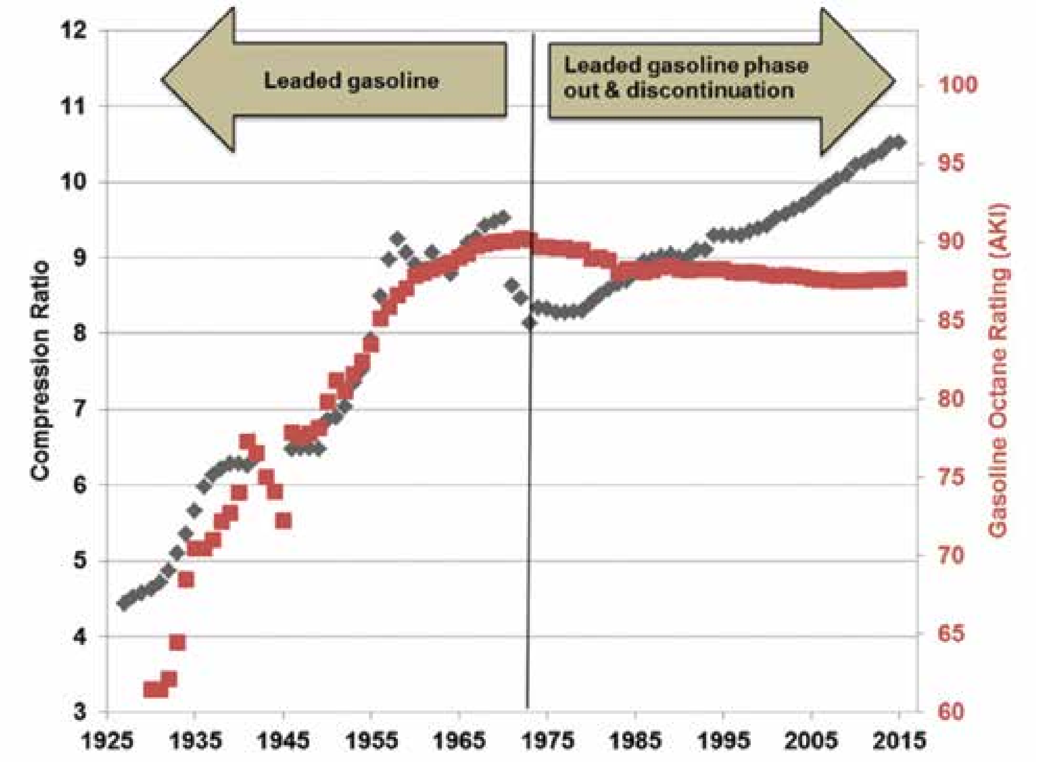
2.4. Ethanol and the efficiency of internal combustion engines

The thermal efficiency of an internal combustion engine indicates how much of the thermal energy released when burning fuel is transformed into mechanical energy, useful for moving a vehicle. In these engines, efficiency depends directly on their compression ratio, which is the relationship between the maximum and minimum volumes of the combustion chamber during the reciprocating movement of the piston in the engine cylinder. Higher compression ratios allow higher efficiencies; however, in gasoline engines operating on the Otto cycle with spark ignition, compression ratios are limited by the octane rating of the fuels used.

Over the past century, when gasoline engines were widely adopted in automobiles, engine designs became more efficient due to increased compression ratios, at the same time that petroleum refineries raised the octane rating of gasoline, by adopting additives, mainly tetraethyl lead, which increased resistance to detonation, essential for optimising the efficiency of these new engines.

This context changed from the mid-1970s onwards, when environmental agencies began to impose stricter limits on emissions and to prevent the use of polluting additives, as shown in Graph 11. Brazil, precisely because it uses ethanol, was one of the first countries to ban the use of lead compounds as additives to improve the octane rating of gasoline.

GRAPH 11. Evolution of the compression ratio of gasoline engines (in black) and the Octane Index (AKI=(RON+MON)/2) (in red) from 1925 to 2015



Source: EIA (2016).

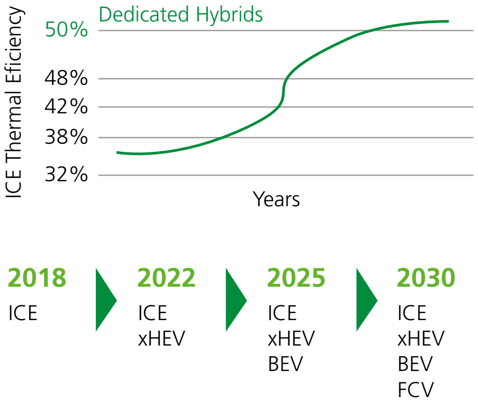
In recent decades, the technological development of combustion engines, especially with the incorporation of digital electronic monitoring and control systems, has enabled further increases in engine efficiency, which are reinforced by the use of high-level ethanol blends or pure ethanol. Thus, ethanol opens a new cycle of technological innovations for internal combustion engines. The higher level of efficiency and low levels of emissions may contribute to a reassessment of decisions to ban or restrict the sale of vehicles with this type of engine in some countries.

2.4.1. New trends in combustion engine designs

The trend towards compact engines with small displacement, supercharging, and direct fuel injection into the combustion chamber has predominated in recent launches by automakers. This technology enables high torque at low speeds, improving drivability and reducing both fuel consumption and exhaust emissions.

Hybrid vehicle electrification enables modern combustion engines to operate in an optimised manner, at specific points of high thermal efficiency. Engines developed specifically for hybrid vehicles from 2022 onwards have evolved so rapidly that, by 2025 they are expected to reach 50% thermal efficiency (Nissan, 2021). These important advances demonstrate that modern internal combustion engines still have significant technological development potential and should no longer be considered an end-of-life technology, but rather as essential elements for the rational electrification of mobility, as shown in Figure 7.

FIGURE 7. Evolution of combustion engine efficiency in hybrid vehicles and diversification of propulsion systems



Powertrain types

Vehicle without electrification:

ICE – Internal Combustion Engine

Vehicle with electrification:

xHEV – Hybrid vehicles without external electric recharging (HEV) and with external recharging (PHEV)

BEV – Pure Electric Vehicle

FCV – Fuel Cell Vehicle

Source: Prepared by Ricardo Abreu.

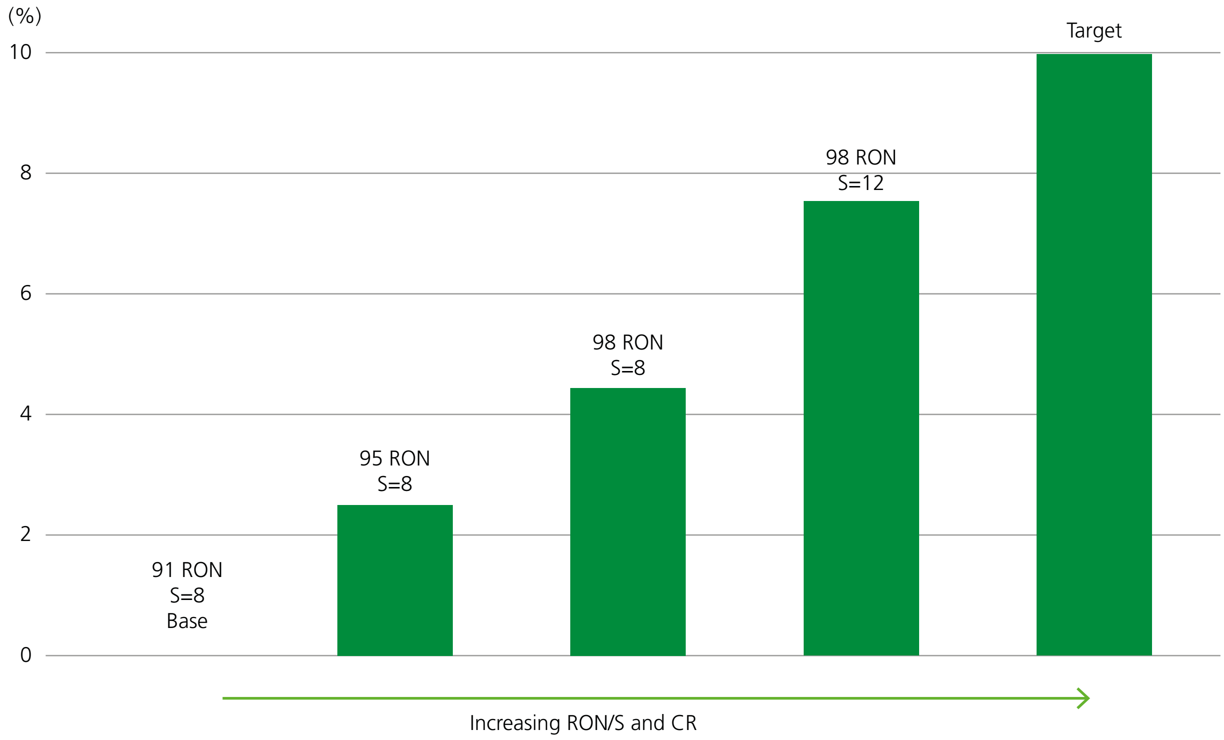
Among the initiatives aiming to jointly optimise engines and energy sources (electricity and fuels), the Co-Optima project stands out (Farrell *et al.*, 2020), developed by the United States Department of Energy. This project innovated in the way of evaluating and classifying energy sources for mobility, adopting the premise that these inputs should reduce greenhouse gas emissions by at least 60% when blended with fossil fuels at levels of up to 30%.

The combination of key properties for the efficient combustion of various fuels was organised into a holistic decision matrix, enabling the selection of the best alternatives in terms of technical performance, toxicological profile, production characteristics, and compatibility with the existing distribution and marketing network. This comparative assessment ranked ethanol as the most promising option for short and medium-term use in modern engine designs.

An important contribution of this study was to demonstrate that the octane rating measured by the research method, RON, is more representative for modern engines than that measured by the motor method, MON. This led to the proposal of a new property, sensitivity (S), defined as the difference between RON and MON values. High sensitivity is essential for improving the efficiency of supercharged engines with direct injection and spark ignition, popularly known as Otto cycle engines. However, today these engines often operate with more efficient thermodynamic cycles, such as the Atkinson or Miller cycles, which are refinements of the Otto cycle.

The high RON (allowing high compression rate—CR), greater sensitivity, and high latent heat of vaporization constitute a unique combination of properties found in pure ethanol and its blends, which particularly favour the efficiency of combustion engines, as shown in Graph 12.

GRAPH 12. Effect of increasing RON and fuel sensitivity (S) on the effective thermal efficiency of combustion engines



Source: Farrell *et al*. (2020).

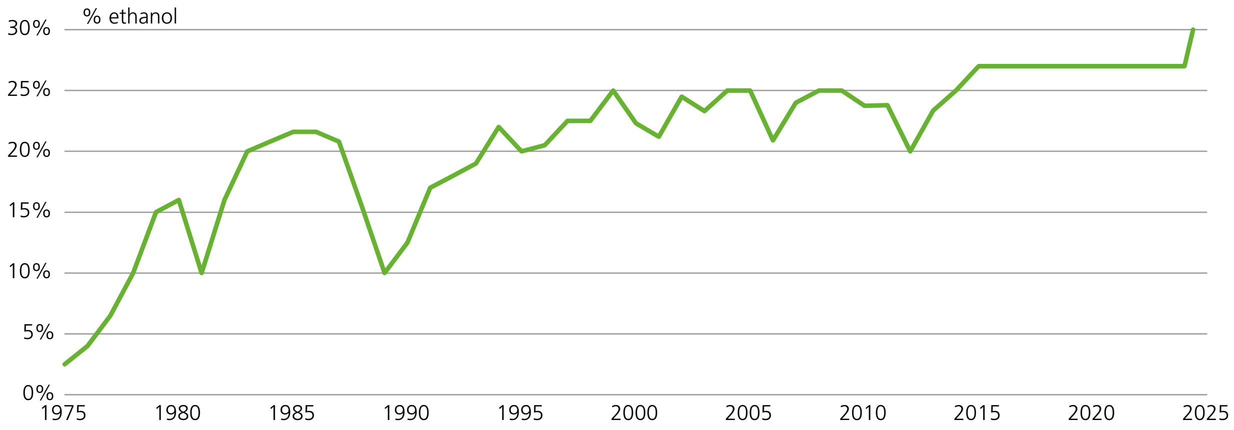
In this study, the E30 blend showed properties considered sufficient to optimise the performance of today's supercharged direct injection engines. When combined with the appropriate 6- to 8-speed transmission to reach optimal torque at low rpm, it provides efficiency gains of up to 10% compared to E10 gasoline.

In Brazil, prototype engines and research conducted at universities and by manufacturers using E100 have shown increases in thermal efficiency and power (average effective pressure). These gains make it possible to replace a 2.4-litre engine used in a 7-seater SUV with a significantly smaller 1.4-litre engine, resulting in an 18% reduction in fuel consumption (Baêta *et al*., 2015). The improved performance partially offsets the reduced range caused by ethanol's 30% lower calorific value compared to gasoline. Brazil's experience with high levels of ethanol content in gasoline and with E100 in flex-fuel vehicles has driven engine evolution, leading to performance gains that represent a significant environmental and economic victory, an evolution that has been progressively adopted by the global automotive industry.

2.5. The Brazilian experience with high bioethanol blends

It is interesting to observe how the bioethanol content in gasoline has evolved in Brazil over time. For more than four decades, Brazil has been adding more than 20% ethanol to gasoline, as shown in Graph 13. The variations observed from 1990 to 2010 were determined by the Brazilian Government based on the availability of bioethanol and the market for sugarcane products. In 2002, the limit for adding ethanol to gasoline was raised to 25%. In 2015, Brazil adopted a mandatory blend of 27% anhydrous ethanol in all regular and additive gasoline sold in the country, used in a fleet of around 45 million cars and 21 million motorcycles, mostly powered by gasoline engines.

GRAPH 13. Evolution of the anhydrous ethanol blend in gasoline since 1975



Source: Prepared by the authors based on BNDES & CGEE (2008); EPE (2024a) and MAPA (2023).

The increase in the blend limit from 25% to 27% was made possible by a testing programme coordinated by the Brazilian Ministry of Mines and Energy and carried out by the Petrobras Research Centre (CENPES), the National Association of Motor Vehicle Manufacturers (ANFAVEA), and the Brazilian Association of Manufacturers of Motorcycle, Moped, Scooter, Bicycle, and Similar (ABRACICLO).

The tests culminated in a final report presenting the results of tests conducted to evaluate the effects of increasing the percentage of anhydrous ethanol in automotive gasoline. Emissions, range, track, and engine performance were analysed, as well as the fuels' physical and chemical properties.

For the emissions and fuel autonomy tests, four gasoline blends were formulated with different ethanol contents (E22, E25, E27.5, and E30). These blends were tested in selected cars and motorcycles that represent different phases of Brazil's vehicle emission control programme for cars (PROCONVE) and for motorcycles (PROMOT), together covering 96% of the circulating fleet powered by gasoline in Brazil at the time.

The main conclusions of the tests were:

- For the vehicles, hydrocarbon, CO, and CO_2 emissions were maintained or reduced with the increase in ethanol content, although a trend toward reduced autonomy was identified.
- In the motorcycle tests, total hydrocarbons (THC) and CO emissions generally decreased as the ethanol content increased, with no clear trend for CO_2 or autonomy. Some cases showed an increase in NO_X, but still within the limits set by environmental legislation.
- On-track performance tests indicated few significant variations in performance for both vehicles and motorcycles.
- The evaluation of the fuels' physicochemical properties showed results within the uncertainty range of the experimental methods and no significant impact from increasing the ethanol content from 25% to 27.5%.

The report concluded by highlighting the effects observed with the use of E27.5 gasoline compared to E25, emphasizing the acceptability of this blend in the tested vehicles and motorcycles and approving its use in the Brazilian fleet. Subsequently, due to the accuracy of the blend content control equipment, which is mandatory at fuel stations, 27% ethanol blend was adopted without issue.

2.5.1. Introduction of E30 in the Brazilian gasoline

In 2024, the Fuel of the Future Law, discussed further, was unanimously approved by the Brazilian Congress and enacted in October 2024 by the Federal Government as Law 14,993/2024. This initiative created the possibility of increasing ethanol blends up to 35% (E35), starting with E30, subject to proof of the technical feasibility of this fuel in the existing vehicle fleet.

With this aim, E30 compatibility tests were conducted in the first quarter of 2025 by the Mauá Institute of Technology, a respected independent engine research centre. The same principles used in 2015 for the approval of E27 were applied to verify E30's compatibility via laboratory and track tests, using representative models of the Brazilian fleet (16 passenger cars and 13 motorcycles) with varying levels of technology. Indicators of drivability, performance, cold starting, idle stability, acceleration, and vehicle emissions were evaluated and analysed.

As in the E27 study, the methodology and testing protocols were endorsed by several entities from the automotive sector, including the National Agency of Petroleum, Natural Gas and Biofuels (ANP), the National Association of Automotive Vehicle Manufacturers (ANFAVEA), the Brazilian Association of Manufacturers of Motorcycle, Moped, Scooter, Bicycle, and Similar (ABRACICLO), the Brazilian Association of Automotive Vehicle Importers and Manufacturers (ABEIFA), and the National Union of Automotive Components (SINDIPEÇAS).

The results consistently indicated that vehicles fuelled with E30 displayed similar behaviour to those using E27 gasoline, demonstrating that electronic control and electronic injection systems—including carburetted models—adapted to the new fuel. Thus, the adoption of E30 gasoline can proceed without harm to consumers and in compliance with environmental requirements.

These studies served as the basis for deliberations by the National Energy Policy Council (CNPE), which approved in June 2025 an increase in the ethanol content of Brazilian gasoline to 30% and recommended that the ANP revise gasoline specifications, raising the RON octane rating from 93 to 94. Premium gasoline, RON 96, used in imported high-performance vehicles, represents a small portion of national consumption and remains at E25. By demonstrating the technical feasibility of E30 and promoting its effective adoption, Brazil has enhanced the national energy security and reinforced the decarbonisation of transport.

2.6. The use of bioethanol in small aircraft and motorcycles

The widespread use of hydrous ethanol as a fuel in small aircraft for general aviation and agricultural applications is a reality within Brazil's agribusiness sector. This confirms the suitability, performance, and safety of using this fuel in alternative aeronautical engines. In 2022, 1,516 agricultural aircraft, 63% of the Brazilian fleet, were operating on pure hydrous bioethanol (SINDAG, 2022).

FIGURE 8. Embraer Ipanema 203 agricultural plane running on hydrous ethanol

Photo: Embraer.

The adoption of bioethanol in aircraft engines began decades ago, initially in blends and later as hydrous bioethanol, following aviation industry certification protocols. In 1989, the US Federal Aviation Administration (FAA) certified an aircraft engine for ethanol use for the first time (Lycoming IO-540, fuel injected), and in the following years certified another engine (Lycoming O-235, carburetted) and two aircraft models, the Cessna 152 and the Piper Pawnee (an agricultural aircraft), for use with anhydrous ethanol containing 5% gasoline (E95) (BIAS, 2006).

In 2005, Embraer, a Brazilian aeronautical company, launched the Ipanema, an agricultural aircraft specifically developed and regularly certified to use hydrous ethanol. In the same year, the company also began supplying kits for converting gasoline-powered agricultural aircraft to ethanol. The Ipanema family of aircraft has since become consolidated and today holds the largest market share in the segment. Now in its fifth generation, the Ipanema line launched the EMB-302 model, featuring several improvements that ensure high productivity and the lowest operating cost in its category using bioethanol (Embraer, 2022). Under Brazilian conditions, bioethanol-powered aircraft have a fuel consumption about 30% higher than those operating on gasoline, but the difference in prices between these fuels results in final savings of up to 60% in fuel costs (Souza & Henkes, 2021).

Bioethanol is also widely used in motorcycles in Brazil, following the introduction of flex-fuel engines in these vehicles. In 2009, Honda launched the CG 150 Titan Mix, the world's first flex-fuel motorcycle, capable of running on ethanol, gasoline, or any mixture of the two. The 2012 YS 250 Fazer BlueFlex was Yamaha's first flex-fuel model, followed by many others from both manufacturers. By 2023, Honda had sold 8 million 'FlexOne' units and had begun exporting them to India.

Motorcycles have specific requirements for cold starting and smooth running, both of which are linked to rider safety. In addition, the same technology used in four-wheel vehicles had to be adapted to comply with different emissions regulations, which posed additional engineering challenges. Honda, which currently holds a 68% share of the Brazilian market, produces 60% of its motorcycles as flex-fuel models, attesting to the success of this development.

2.7. Emerging technologies for bioethanol use in mobility

2.7.1. Ethanol in diesel engines

The same factors that make ethanol particularly suitable for use in spark ignition engines (Otto cycle) make it less attractive for compression ignition engines (Diesel cycle), which are generally used in trucks, buses, and agricultural machinery. For this reason, although ethanol's thermal efficiency remains similar to that of diesel (approximately 44%), these engines are unable to take advantage of its higher octane rating and consume more ethanol than diesel due to the difference in calorific values between these fuels.

Nevertheless, to extend the environmental advantages associated with the use of ethanol in diesel engines, technologies have been researched since the 1980s to make its use viable. Some studies have considered the use of blends of up to 15% ethanol in diesel oil. Technical feasibility and a reduction in particulate emissions have been demonstrated, as well as difficulties with stability and the need for co-solvents (Hansen *et al.*, 2005).

An alternative that has proved more promising is the use of additives in hydrous ethanol to increase its lubricating power and its cetane number, a property that indicates the tendency of a fuel to burn when compressed. According to the tests perfomed in the Alcohol Application in Compression Ignition Engines Project, conducted under the leadership of the Technical University of Denmark (AMF, 2018), ethanol with proper additives can be used in diesel engines with very high compression ratios (28:1), with high efficiency and a significant reduction in particulate emissions.

Adopting this concept, and redesigning the injection, combustion, and emissions systems, Scania currently manufactures 9-litre (270 HP) and 13-litre (410 HP) engines for the fuel called ED95, composed of 95% hydrous ethanol with an ignition improver, corrosion inhibitor, and denaturants produced by the Swedish company SEKAB (Scania, 2019).

FIGURE 9. Truck with diesel engine powered by hydrous bioethanol with additives

Photo: Peggy Bergman/Scania.

In Brazil, as early as the 1980s, various studies were conducted into the use of ethanol in diesel engines, with the aim of meeting the fuel demand of the sugar and ethanol industry's large fleet of trucks and agricultural machinery, with economic and environmental benefits (Sopral, 1983). Until recently, the use of ethanol additive in diesel engines with electronic injection and a high compression ratio was the predominant innovation considered for sugarcane logistics. However, in recent times, biomethane has also been considered as an option. This fuel is cheaper and produced in the mill itself from vinasse biogas and filter cake, but it is difficult to sell or transport over long distances. The use of biomethane replaces diesel and thus reduces the carbon footprint of the ethanol produced at the plant, as presented further.

The search for a low-carbon substitute for diesel oil has recently generated a revitalization of research and experiences by several manufacturers with the use of ethanol in heavy-duty engines, normally adopting the Diesel cycle. Recently, Finnish company Wärtsilä, which produces dual-fuel engines for ships that can operate on diesel or methanol, started a collaboration with Raízen to test ethanol as an alternative fuel in these engines. The expectation is to reduce CO_2 emissions by up to 80% on a standard route from Brazil to Europe. John Deere, a manufacturer of equipment for the agricultural, construction, and forestry sectors, presented at the Agritechnica 2023 world agricultural machinery fair in Hanover, at the end of 2023, the prototype of a 9.0 L ethanol engine.

The mining company Vale, which in its operations in Brazil consumes around one billion litres of diesel per year, half in railway locomotives and half in high-powered off-road trucks, signed an agreement with Komatsu and Cummins to develop and test off-road trucks powered by a mixture of ethanol and diesel, as part of initiatives to meet emissions reduction targets in the coming years. Around 80 trucks, with a capacity ranging from 230 to 290 tonnes, should receive two tanks, one for ethanol and the other for diesel. The mixing of both fuels will take place inside the truck, during its operation. The adapted trucks will use up to 70% ethanol in the mixture, estimating a reduction in direct CO_2 emissions of up to 70% compared to diesel-only vehicles.

2.7.2. Ethanol in fuel cells

Electric vehicles present significant advantages over vehicles with internal combustion engines: they do not need gearboxes and can regeneratively recover the kinetic energy dissipated during braking. Depending on the source of the electricity that powers their motors, electric vehicles can be battery-powered (BEV) or hybrid (HEV).

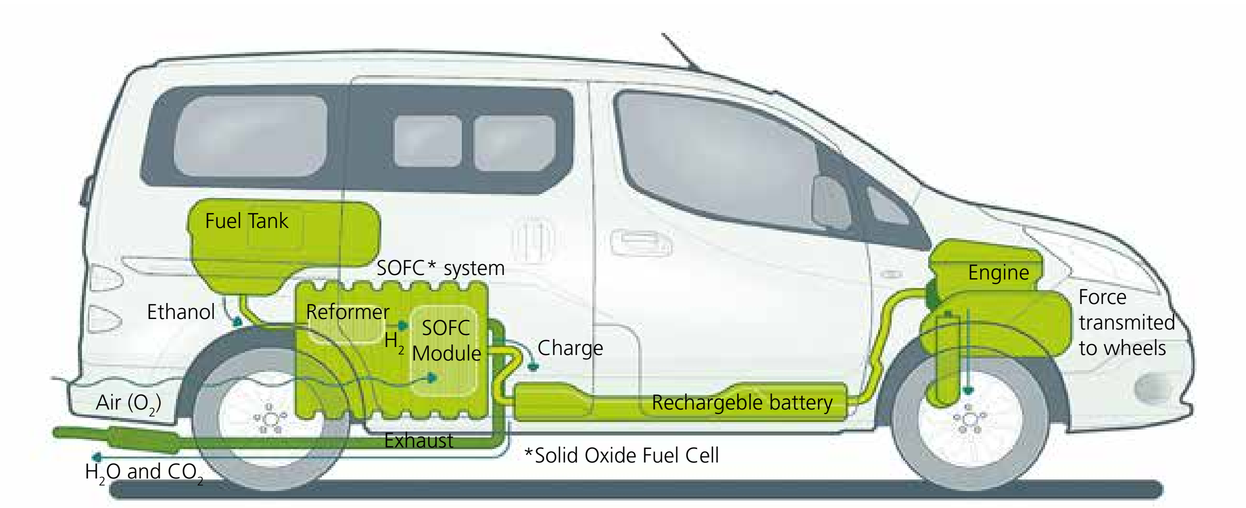
In battery electric vehicles, the electrical energy stored in these devices is supplied by external sources, such as the distribution network. In hybrid electric vehicles, the electricity is produced in the vehicle itself, usually by generators driven by combustion engines operating under efficient conditions. As already seen, hybrid vehicles have advantages in that they combine the electric drive of the wheels with the generation of onboard electricity, significantly reducing the weight and capacity required of the batteries, refuelling time and the demand for critical materials, as well as avoiding dependence on the electricity transmission and distribution infrastructure and being able to use the fuel distribution logistics already in place (Gonçalves *et al.*, 2022).

Another possibility for generating electricity for mobility is the fuel cell, usually the hydrogen fuel cell, which operates silently, with few moving parts, and can convert the chemical energy of fuels directly into electrical energy, with efficiency greater than thermal cycles. They can therefore be interesting alternatives to combustion engines in hybrid electric vehicles. The use of ethanol directly in fuel cells is still under development, but the use of ethanol as a "hydrogen carrier," which is produced in a reformer and then used in fuel cells, has advanced.

For fuel cell applications in ethanol mobility, solid oxide fuel cells (SOFCs) have been used, which despite their low structural strength and operating temperature above 600°C making cold starting difficult, are less demanding in terms of hydrogen purity and CO contamination. Moreover, the SOFC can provide heat for ethanol reforming, which increases thermal efficiency. Catalytic steam reforming of ethanol (ESR) in metal-based cells improves their stability and mechanical properties.

Progress has been made in integrating the ethanol reformer into the SOFC cell, a concept known as internal reforming. Nissan reported that the successor to the first SOFC-powered vehicle, which was presented in Brazil in 2016, already has a new version in testing that incorporates this advance with encouraging results (Zaparolli, 2021).

FIGURE 10. Nissan e-Bio electric ethanol vehicle



Source: Adapted from IPEN and Nissan, as cited in Zaparolli (2021).

3.

Bioethanol production

Decepar a cana
Recolher a garapa da cana
Roubar da cana a doçura do mel
Se lambuzar de mel
Afagar a terra
Conhecer os desejos da terra
Cio da terra propícia estação
E fecundar o chão

Cut the cane
Gather the cane's sweet juice
Steal from the cane the sweetness of honey
And revel in that honey
Caress the earth
Learn the earth's desires
The earth's fertile season, ripe for sowing
And make the soil fruitful

Milton Nascimento and Chico Buarque,
Cio da Terra (*Earth heat*), our translation.

Similar to the production of alcoholic beverages, bioethanol production for energy and industrial purposes can also make use of various plant-based materials containing chemical energy, composed of carbohydrates synthesised from solar energy, water, and carbon dioxide: sucrose, starch, and cellulose, molecules composed solely of carbon, hydrogen, and oxygen atoms. Sucrose is primarily found in sugarcane and sugar beet; starch is present in cereals like maize, wheat, and rice, and in tubers such as potatoes and cassava; while cellulose is found in the stems and leaves of most plants.

Sucrose and starch are stored in plants as energy reserves, whereas cellulose primarily serves a structural function. However, these substances derive from a single biomolecule: glucose ($C_6H_{12}O_6$), which adopts increasingly complex structural forms. Sucrose consists of just two molecules, glucose and fructose, which share the same chemical compositions but different structures. Starch is a polymer composed of hundreds of glucose molecules and their dehydrated derivatives. Cellulose, by contrast, is a linear polymer with long chains consisting only of glucose. The accessibility of glucose within the biomass determines the industrial process required.

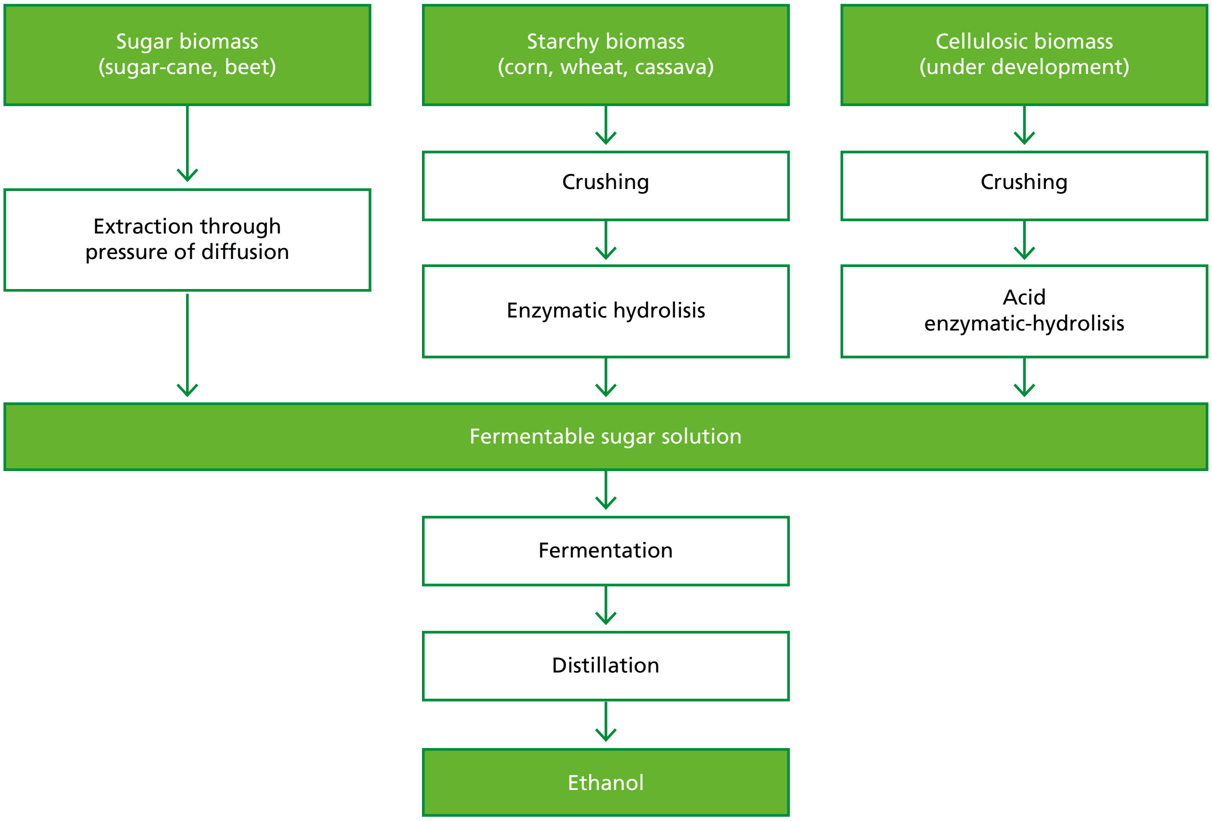
Therefore, as shown in Figure 11, different types of biomass must be processed via specific technological methods to release the simple sugars in their composition and yield fermentable solutions, which are essentially glucose in water. During alcoholic fermentation, yeast acts on these solutions, releasing some of the carbon dioxide absorbed during photosynthesis and transforming them into alcoholic solutions. Distillation of these solutions yields bioethanol, which can be used as a fuel.

In real-world conditions, small quantities of by-products may be produced during fermentation, but the simplified conversion of glucose into ethanol or bioethanol can be represented by the following equation.

$$C_6H_{12}O_6 \rightarrow C_2H_6O + 2\ CO_2 \tag{2}$$

Thus, in terms of mass, the fermentation of 180g of glucose yields 92g of bioethanol and 88g of carbon dioxide. It is interesting to compare this fermentation reaction with the photosynthesis equation presented in the first chapter of this book: glucose stores solar energy, and through fermentation, this solar energy becomes available in the form of bioethanol.

FIGURE 11. Bioethanol production technological pathways

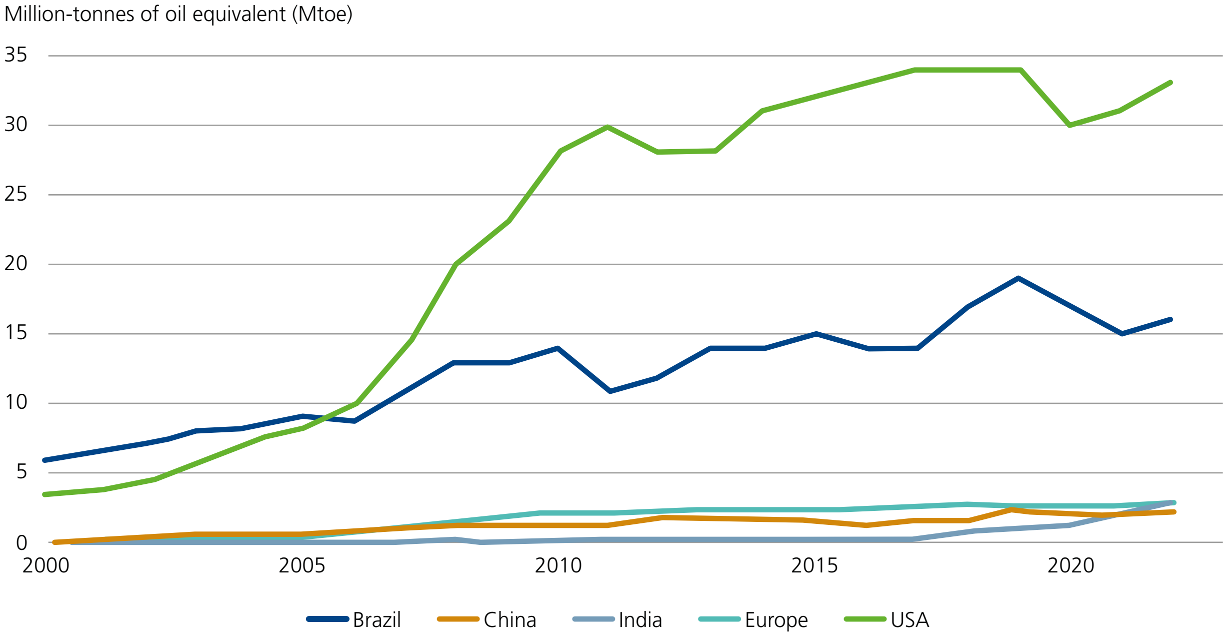


Source: Prepared by L. A. Horta Nogueira.

Among liquid biofuels, bioethanol stands out as the most mature alternative and for its effective integration into the energy matrices of several countries. In 2021, global liquid biofuel production reached 162 billion litres (4.06 EJ), with bioethanol accounting for two-thirds of that total. The remainder derived from various biomass-based diesel types, such as biodiesel and hydrotreated vegetable oil (HVO) (REN21, 2024).

Until recently, bioethanol production was concentrated in the United States, using maize as the raw material, and in Brazil, using sugarcane. These two countries accounted for over 80% of global bioethanol production and consumption. In recent years, however, this scenario has begun to shift, with increasing bioethanol production and consumption in several European countries, particularly France and Belgium, where wheat and sugar beet are processed (USDA, 2024). The gradual evolution of the bioethanol market in China and the growing demand in India, as shown in Graph 14 (EIA, 2024a), are also noteworthy. In some emerging Asian markets, maize and rice have been the most commonly used raw materials, with a smaller contribution from sugarcane and cassava. In all cases, the agricultural phase, from planting to harvesting and transporting the raw material to the processing plant, represents the highest cost in biofuel production.

GRAPH 14. Evolution of global bioethanol production



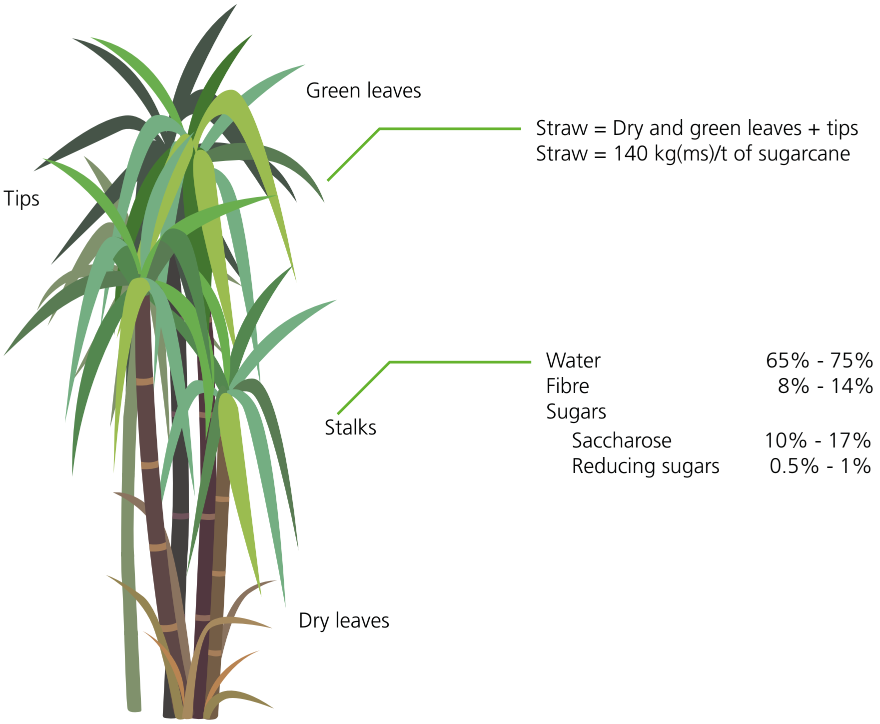
Source: Prepared by the authors based on EIA (2024a).

The following sections cover the fundamental principles of industrial production and processing of sugarcane and maize, the two primary raw materials used to produce bioethanol. Then, the production of bioethanol from lignocellulosic residues, such as straw from various crops, is introduced, focusing on processes refined over recent decades. This technology has reached the commercial stage in recent years. At the end of the chapter, the technologies applied to other raw materials, such as cassava and sorghum, are briefly presented.

3.1. Sugarcane Bioethanol

Sugarcane is a semi-perennial plant with a C4 photosynthetic cycle, belonging to the genus *Saccharum*, part of the grass family (*Poaceae* or *Gramineae*). It consists of tall grass species that originate from warm temperate to tropical regions of Asia, particularly India. The aboveground part of the plant is mainly composed of the stalks, where sucrose is concentrated, and the tips and leaves, which form the cane straw, as shown in Figure 12. Altogether, these components amount to approximately 35 tonnes of dry matter per hectare.

FIGURE 12. Typical composition of sugarcane biomass



Source: Adapted from Seabra (2008).

Sugarcane is one of the most important commercial crops worldwide, accounting for most of the global sugar production, which reached 180 million tonnes in 2023. According to estimates from the Food and Agriculture Organisation (FAO), the sugarcane crop occupied 26 million hectares across 93 countries from 2020 to 2022, yielding an average of 1.89 billion tonnes per year over the last three harvests.

The five largest producers of sugarcane—Brazil, India, Thailand, Colombia, and Guatemala—together account for 74% of global production. Table 4 presents the 12 leading sugarcane producers for the 2020 harvest, ranked by productivity in tonnes of wet stalk per hectare (t/ha) (FAO, 2024).

TABLE 4. Basic data on sugarcane cultivation in main producing countries, 2020

COUNTRY	PRODUCTION (MILLION T)	AREA (THOUSAND HA)	YIELD (T/HA)
Guatemala	27.7	246	112.7
Colombia	36.4	408	89.2
United States of America	32.7	383	85.4
Australia	30.3	366	82.6
India	370.5	4,603	80.5
China	108.7	1,362	79.8
Brazil	756.1	9,996	75.6
Indonesia	29.3	419	69.9
Pakistan	81.0	1,165	69.5
Mexico	53.8	775	69.5
Philippines	24.4	399	61.1
Thailand	75.0	1,714	43.7

Source: Prepared by the authors based on FAO (2024).

3.1.1. The sugarcane crop

The ideal climate for cultivating sugarcane features two distinct seasons: a warm and humid one to support germination, tillering, and vegetative growth, followed by a cooler and drier season to promote maturation and the consequent accumulation of sucrose in the stalks. Sugarcane does not thrive in the climates of humid equatorial regions, which is why it makes little sense to consider the Amazon for extensive commercial cultivation of this plant.

Sugarcane is a semi-perennial plant with annual harvests, followed by regrowth from the stubble—the part of the plant with roots that remains in the soil. The number of successive cuts and regrowths depends on the climate, varieties, and cultural practices. In Brazil, the typical cycle lasts around six years, during which there are five cuts, four stubble treatments, and one renovation or replanting, as explained below. Generally, the first cut occurs 12 to 18 months after planting (depending on the variety of cane used), when the so-called plant cane is harvested.

The subsequent cuts, in which the regrowth known as ratoon cane is harvested, occur once a year over the next four consecutive years, with a gradual reduction in productivity until it becomes economically more viable to renovate the sugarcane field rather than take another cut. At that point, the old cane is removed and replaced with a new planting, initiating a new production cycle. During this renovation, the cultivated area rests for a few months and may host other short-cycle crops, such as legumes, which contribute to soil fertility.

The continuous renewal of sugarcane fields and the appropriate selection of productive and resistant varieties are essential factors for maintaining productivity. In this regard, the ideal share of plant cane (the area newly planted in each year relative to the total area of sugarcane fields in production) is considered to be 18%, which corresponds to field renewal after five harvests. A lower rate of renewal implies a higher average age of the sugarcane field and reduced productivity.

According to the sugarcane production cycle, achieving stable production across various harvests and rationalising resource use in the agricultural stage (machinery and labour) requires subdividing production areas into plots at different stages of the cycle, corresponding, for a six-year cycle, to about one-sixth of the total area in each stage. Another consequence of this production cycle is that, when establishing a sugarcane bioethanol production unit, agricultural activities should begin two to three years before actual industrial production, initially to multiply seedlings and ensure a relatively stable supply of raw materials within three to four years, by the time the industrial process is operational.

Sugarcane varieties have been the subject of ongoing breeding programmes aimed not only at improving sugar productivity but, more recently, at increasing fibre yield, resistance to diseases and water stress, delayed flowering (a plant process that consumes accumulated sugar), and suitability for mechanical harvesting, among other traits, within specific soil and climate conditions, as well as promoting desirable genetic diversity renewal.

The maturation time of sugarcane is also important to ensure harvesting occurs at peak sugar content. Through proper varietal planning, effectively combining early, mid-season, and late-maturing varieties, it is possible to utilise industrial processing capacity over a longer period with high-quality raw materials.

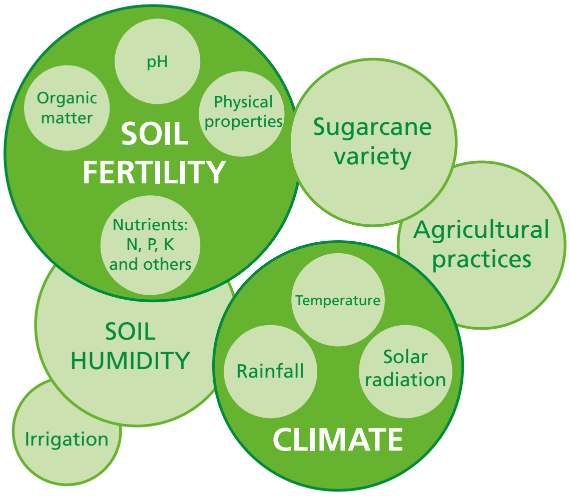
It is noteworthy that, as the typical sugarcane production cycle involves five cuts over six years, the average annual productivity must also account for the period of field renovation. Moreover, since a portion of the cane produced (about 8%) is allocated to the renovation (replanting) of sugarcane fields, the annual productivity measured in tonnes of cane effectively processed per planted hectare is lower than the total productivity assessed in terms of harvested cane.

The harvest period, known as the sugar year, varies by country; in Brazil, it begins in April and ends in March of the following year. Within this framework, in the most recent harvests, 2022/2023 and 2023/2024, the average productivity of Brazilian sugarcane fields was 73.7 and 85.6 t/ha, respectively, representing a significant increase attributed to favourable climatic conditions. In the latest harvest, the Centre-South region[1], which accounts for 91% of Brazil's total sugarcane production, achieved a productivity higher than the national average, at 88.2 t/ha, while the North-Northeast region, with less field renewal and less favourable climate, produced 64.8 t/ha (CONAB, 2024b).

3.1.2. The importance of climate, water availability and soil fertility

Similar to other agricultural crops, sugarcane productivity is impacted by several factors, as shown in Figure 13. In some cases, these factors can be adjusted or improved via human intervention and appropriate agricultural practices, such as irrigation to compensate for low soil moisture and fertilisation to maintain soil fertility.

FIGURE 13. Sugarcane: main productivity factors



Source: Adapted from IRENA (2019).

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[1] The Centre-South (Centro-Sul) of Brazil is a socioeconomic concept, not an official division, encompassing São Paulo, Paraná, Santa Catarina, Rio Grande do Sul, Minas Gerais, Mato Grosso do Sul, and parts of Goiás and Mato Grosso, where most of the nation's agriculture and industry are concentrated.

To estimate sugarcane productivity under different climatic conditions while using appropriate agricultural practices, the most important parameters related to climate and soil moisture are (Valade *et al*., 2014):

- The frequency and intensity of hot days, assessed by the annual thermal time for heating or degree-days, estimated as the accumulated product of the average daily temperature and the number of days above a threshold temperature required for efficient photosynthesis (assumed to be 20°C). This value is now available in various meteorological databases.
- Water available to the sugarcane root system in the soil, or water deficit, measured in litres or millimetres of water per square metre at a depth of one metre. This is estimated via the soil water balance, considering water inputs (rainfall) and outputs from a column of soil (evapotranspiration from the sugarcane plant during its growth cycle, surface runoff, and groundwater recharge). When available water in the soil is lower than the outputs over a given period, a water deficit occurs, which can happen even in regions with high rainfall concentrated in just a few months of the year.

Based on a yield model developed and calibrated with data from sugarcane fields in São Paulo, Beauclair (2014) proposed a simplified model to estimate sugarcane productivity in similar edaphoclimatic contexts:

$$Y = 80.0 + 0.01\,DD - 0.1\,DH \tag{3}$$

In which:

Y = Average productivity in the production cycle (t/ha)
DD = Thermal time or degree-days in relation to 20°C (°C.day)
DH = Annual water deficit, non-existent under proper irrigation (mm)

Under optimal fertility and water availability conditions, sugarcane develops deep roots, which contributes to increased productivity by enhancing the volume of soil utilised for extracting water and nutrients. In areas with rainfall exceeding 800 mm (ideally from 1,200 mm and 1,500 mm), adequately distributed with well-defined wet and dry seasons, water availability is considered sufficient to achieve good productivity in properly managed sugarcane fields, ranging from 80 to 100 t/ha. Additionally, in typical producing units in Brazil's Centre-South region, where half of the sugarcane is used to produce sugar and the other half for bioethanol, the application of vinasse (via fertigation) represents about 15 to 20 mm across 30% of the fields, effectively eliminating the need for irrigation.

FIGURE 14. Sugarcane roots

Photo: Rafaella Rossetto.

However, in areas with lower water availability, particularly during the early growth stages of the sugarcane plant, when the root system is still developing, the practice known as 'rescue irrigation' has been justified. This is applied during the initial growth phases. In sugarcane fields in Brazil's Central-West region, where dry spells lasting several months frequently occur, this type of irrigation has been employed, with water in limited quantities—typically two or three irrigations of 60 millimetres per month after planting—resulting in significant productivity gains, reaching 200 t/ha in the first harvest (EMBRAPA, 2022a).

Another critical factor for sugarcane productivity is soil fertility, which must be properly managed. Soil amendments and fertilisers are crucial inputs for sugarcane production and should be applied in the correct quantity and at the appropriate time, in an economically and environmentally responsible manner.

Lime is commonly used to correct soil acidity and extend the productive lifespan of sugarcane fields, while gypsum aids mitigate the harmful effects of aluminium and adds calcium to deeper soil layers.

To meet the nutritional needs of sugarcane, fertilisation should be based on the characteristics of the cultivated soil and the nutrients required for fertility and proper crop development. The most important elements for plants—nitrogen (N), phosphorus (P), and potassium (K)—are known as macronutrients (NPK), supplemented by smaller amounts of mineral nutrients such as calcium (Ca), magnesium (Mg), and sulfur (S), among others.

Nitrogen is essential for sugarcane growth and rooting; however, its impact on overall productivity is relatively minor. Nonetheless, from 30 to 60 kg of nitrogen in various formulations are applied per hectare. In ratoon crops, productivity is strongly influenced by nitrogen application, typically ranging from 80 to 150 kg/ha, depending on the production environment, variety, and age of the sugarcane field.

Potassium is required in larger quantities, with applications from 80 to 150 kg of K_2O per hectare for both plant cane and ratoon crops (EMBRAPA, 2022a). In areas where vinasse is applied, potassium is supplied via fertigation (UDOP, 2022), providing significant benefits to soil health by increasing organic matter and improving physical properties, along with economic advantages (Luz *et al.*, 2024).

Phosphorus is the nutrient that plants require in the smallest amounts. Nevertheless, in Brazilian soils, it must be applied in larger quantities due to its low natural availability. Therefore, phosphate fertilisation is effective in enhancing the productivity of sugarcane fields, particularly in Brazilian soils, which are generally poor in phosphorus. Typical applications range from 100 to 150 kg of P_2O_5 per hectare, usually applied once at planting. This dose of phosphorus is sufficient to meet the crop's needs for five years (EMBRAPA, 2022a).

In addition to conventional fertilisation, green manure has increasingly been adopted during sugarcane field renovation by growing legumes such as soybean, *Crotalaria*, and *Mucuna pruriens* in the months preceding sugarcane planting. These plants fix atmospheric nitrogen in the soil and aid reduce the demand for nitrogen fertilisers (Ambrosano *et al.*, 2011).

FIGURE 15. Green manure in sugarcane field renovation

FIGURE 15A. Direct planting of soybeans in sugarcane residue

Photo: Rafaella Rossetto.

FIGURE 15B. *Crotalaria* in sugarcane seedling planting areas

Photo: Rafaella Rossetto.

3.1.3. Sustainable agricultural practices in sugarcane production

In addition to the irrigation and fertilisation practices discussed in the previous section, several techniques have been developed and progressively adopted to reduce costs, enhance productivity, and preserve soil fertility, as well as to decrease both direct and indirect greenhouse gas emissions. Some of these techniques have yielded positive results, including:

- **Direct seeding:** This method involves operations with a lower impact on land preparation. It has gained momentum with the development of the simultaneous inter-rotational method (MEIOSI), which aims to establish a high-quality nursery for sugarcane seedlings within the same area as the sugarcane field renovation. This provides additional income via intercropping. Immediately after the final harvest preceding the renovation, farmers prepare the land and plant rows of pre-germinated seedlings, referred to as “mother lines,” while leaving up to fifteen inter-row spaces free for economically viable intercrops, such as soybeans and peanuts, or green manures that fix atmospheric nitrogen in the soil. As illustrated in Figure 15b, *Crotalaria* lines flourish between the sugarcane rows. Subsequently, after harvesting these intercrops, sugarcane is planted in the inter-row spaces using cuttings produced from the sugarcane planted in the mother lines within the same area (CTC, 2020).

- **Cultivation of pre-germinated seedlings:** To accelerate sugarcane growth, minimise field gaps, improve phytosanitary conditions, ensure varietal control, and enable mechanisation, the traditional planting method—placing cane stalks into furrows—has increasingly been replaced by the cultivation of pre-germinated seedlings, known as MPB, particularly in the MEIOSI method. These seedlings are essentially "mini cuttings" (small sections of a stalk with just one bud and fractions of the internodes), selected and treated under controlled conditions of sterility, temperature, and humidity, then rooted in containers before being cultivated in renovation areas of the fields. Despite the higher costs associated with MPB—which require investment and training—this technique has proven beneficial and has seen increased adoption over the past decade (EMBRAPA, 2019).

FIGURE 16. Field activities with pre-germinated sugarcane cuttings (MPB) in areas of cane field renewal

FIGURE 16A. Preparation of a sugarcane cultivation line

Photo: Rafaella Rossetto.

FIGURE 16B. Planting pre-germinated sugarcane cuttings

Photo: Rafaella Rossetto.

- **Precision agriculture:** This approach involves the use of advanced technologies to collect accurate data and information about production conditions. These include GPS, soil and climate sensors, drones, and real-time data analysis software. The collected data aid guide land and crop management, optimising agricultural operations while rationalising the use of inputs such as fertilisers and agrochemicals. In sugarcane cultivation, precision agriculture systems have been employed to monitor soil and plant conditions, including pH, moisture levels, and nutrient availability. This monitoring aids in early detection of diseases and pests and enables precise and localised recommendations for fertiliser and pesticide application in appropriate quantities and locations (EMBRAPA, 2014). Consequently, precision agriculture enhances productivity and harvest quality while significantly reducing input usage and resource waste, thereby contributing to the sustainability of bioenergy production from sugarcane.

- **Biological pest control:** This technique employs natural enemies of sugarcane pests, including insects and microorganisms. It is a well-established method that has proven effective in reducing agrochemical use (insecticides and fungicides) in relation to cultivated areas, maintaining application levels below those of most other agricultural products in Brazil. The two primary pests impacting sugarcane are managed via biological control methods: the sugarcane borer (*Diatraea saccharalis*), a moth whose larvae are targeted by the wasp *Cotesia flavipes*, and the sugarcane roothopper (*Mahanarva fimbriolata*), which is controlled using the fungus *Metarhizium anisopliae*.

FIGURE 17. Sugarcane borer (*Diatraea saccharalis*), being attacked by the wasp *Cotesia flavipes*

Photo: Koppert Brasil.

Notably, the techniques discussed above are freely accessible to all sugarcane producers. Their willingness to adopt innovative procedures and processes is crucial for enhancing productivity in sugarcane fields. In this context, the Agronomic Institute (IAC), a leading state institution in São Paulo, has played a significant role in advancing technology and sustainability within the sugarcane industry. As early as 1892, the IAC conducted its first study on sugarcane, which included 42 varieties cultivated under two different conditions.

Focusing its efforts on this crop, the IAC Sugarcane Centre, via the IAC Sugarcane Programme, promotes a multidisciplinary approach that encompasses genetic improvement, soil sciences, production environment characterisation, agronomy, pest and disease management, and production estimation. Building on these foundations, the programme develops and promotes the adoption of technological packages designed to create high-productivity environments tailored to specific contexts and regions.

The IAC Sugarcane Programme systematically monitors sugarcane cultivation across ten regions in Brazil. In its 2023 edition, data were collected from 219 production units, representing 62% of the country's sugar production and 59% of the area cultivated with sugarcane. The results are analysed based on the amount of sugar produced per hectare and the adoption of modern sugarcane varieties, forming the basis for the award of the IAC Productivity and Modernity Prize (IAC, 2023a).

This productivity monitoring—measured in tonnes of sugar per hectare over the first five harvests, along with the average age of planted varieties across different production environments—is vital for guiding agronomic research. It also provides producers with a valuable reference for achievable productivity levels and the requirements and pathways to reach those goals.

A notable example is the Denusa distillery (Destilaria Nova União S.A.), located in the arid climate of Goiás, which reported an average productivity of 50 tonnes per hectare in 2010. Since then, in collaboration with the Agronomic Institute, it has adopted the technological packages developed by the IAC Sugarcane Programme. By 2023, the company led the nation in productivity, reaching 103 tonnes per hectare. This remarkable improvement can be attributed to a shift in the variety base, the establishment of a nursery for pre-germinated seedlings (MPB), the characterisation of production environments, careful monitoring of soil conditions, the adoption of biological pest control, invasive weed management, and the training and engagement of the distillery's personnel (IAC, 2023a).

3.1.4. Harvesting and transporting sugarcane

For centuries in Brazil, sugarcane harvesting was performed manually, requiring a large workforce of temporary labourers. However, this scenario has changed significantly. Today, with few exceptions in areas with steep slopes (above 16 degrees), sugarcane intended for industrial processing is harvested using mechanised harvesters. In much of the country, sugarcane is now harvested in its raw state, meaning it is collected without the prior burning of the cane straw, which is also gathered and transported to the mill, where it serves as a valuable co-product with energy potential. This profound shift in the harvesting method is discussed in Chapter 6: *Integrating processes, circularity and diversity in bioenergy production: the Brazilian model.*

FIGURE 18. Mechanised sugarcane harvesting

Photo: Acervo Copersucar.

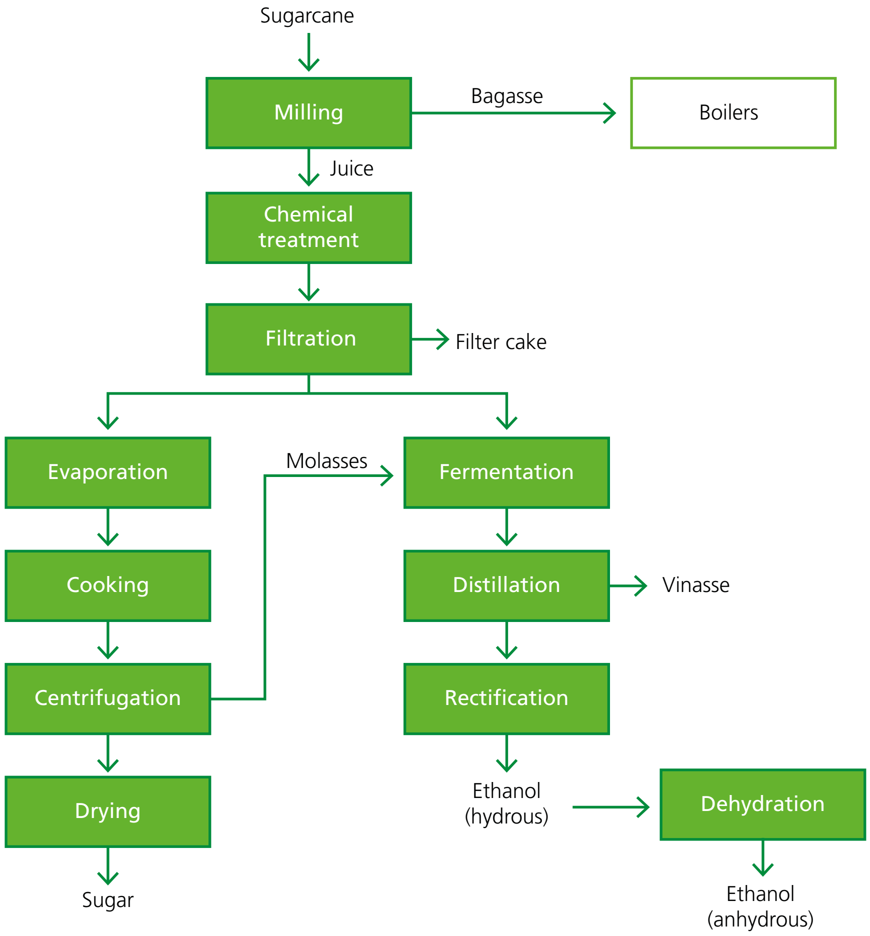
Once harvested, sugarcane is transported to the processing mill as quickly as possible to minimise sucrose losses. Except for a few companies that utilise river or rail transport, the transportation system primarily relies on tractors with trailers and various types of lorries: single-trailer lorries, double-trailer lorries, triple-trailer lorries, and "road trains," lorries pulling several trailers, with total capacities ranging from 15 to 60 tonnes. The choice of transportation method depends on the distance from the production area to the processing unit, the traffic conditions on the transport routes, and, naturally, the operational costs associated with each type of transport.

The operations of cutting, loading, and transport are significant components of the cost of sugarcane and have undergone continuous evolution to reduce costs, preserve the stubble of the sugarcane (the set of shoots or regrowths that emerge from the base of the cane stem after harvest), and minimise soil compaction. In recent years, there has also been a push for the introduction of lorries using alternative fuels to diesel, such as biomethane, produced from the biogas generated as a by-product of bioethanol production, a topic covered later.

With the expansion of the processing capacity of Brazilian sugar-energy plants over the past few decades, the average crushing per harvest has nearly doubled per plant, and the distances for transporting sugarcane have consequently increased. However, these distances depend on the density of the sugarcane crop in the area surrounding the plant. Under conditions observed during the 2005/2006 harvest, for a sample of 44 plants in the Centre-South of Brazil, a typical plant processed 2.3 million tonnes of sugarcane, transported on average over 23 km. In that context, it was possible to infer that the areas of sugarcane production occupied about 7% of the land surrounding the plant. With the recent expansion of the plants to the west, cultivating sugarcane in areas previously dedicated to extensive cattle ranching, it has been possible to increase the density of the sugarcane fields. When occupying 20% of the land close to a plant processing 4.0 million tonnes of sugarcane, the average transport radius for sugarcane was less than 25 km (CGEE, 2012).

3.1.5. Processing sugarcane

FIGURE 19. Stages of sugar and bioethanol production from sugarcane



Source: Seabra (2008).

Since sugarcane cannot be stored for more than a few days, processing plants operate only during the harvest season. The initial stages of sugarcane processing—whether for sugar or ethanol production—are the same, as illustrated in Figure 19. Upon arrival at the mill, the sugarcane undergoes weighing and quality assessment (measuring the sugar content). It is then unloaded and dry cleaned, a process that saves a significant amount of water compared to pre-mechanised harvesting practices. After cleaning, the sugarcane is prepared by shredders to facilitate the next stage: juice extraction.

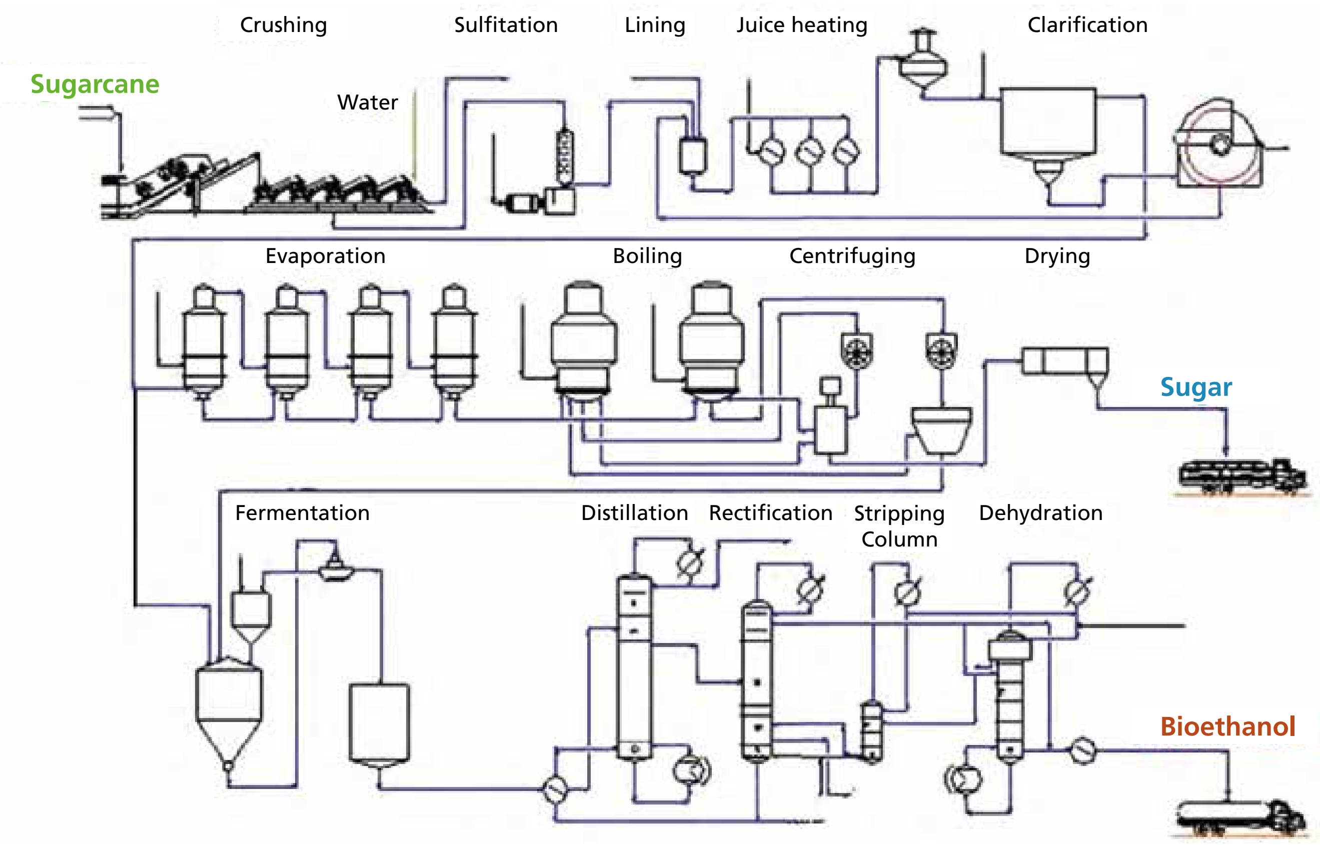
In Brazil, the most widely adopted method of extraction is milling, in which the juice is extracted by pressing the shredded sugarcane between the rollers of a mill. These rollers are arranged in sets, usually comprising four to seven consecutive mill units. To achieve high levels of sugar extraction efficiency, forced feeding systems and imbibition are used. Imbibition involves applying hot water (approximately 250% of the fibre processed) to the bagasse before it reaches the final mill unit. The juice extracted from this process is pumped back to the previous mill unit and continues in a counter-current flow, moving against the flow of bagasse through the mills. In the milling process, the juice containing the sucrose is separated from the fibre (bagasse), which is then directed to the mill's energy plant, where it serves as fuel for the boilers.

In some Brazilian plants, diffusion extraction is also employed, with potential energy advantages. In this process, the sucrose is extracted by washing the shredded sugarcane with hot water through successive stages. The sugar is washed out, and the bagasse, now relatively dry, is passed through a drying roller before being sent to the boilers. However, diffusion extraction has seen limited adoption, mainly due to its lower operational flexibility and the comparable efficiency of modern milling systems. Whether produced by milling or diffusion, the juice extracted from the sugarcane can be directed towards sugar or bioethanol production.

For sugar production, the juice is first screened and chemically treated to promote coagulation, flocculation, and precipitation of impurities. These impurities are removed via juice decantation, and the by-product, filter cake, is often used as fertiliser, particularly for newly planted sugarcane fields. The filter cake results from the recovery of sugar from the decanter sludge through vacuum rotary filters.

The clarified juice is then concentrated in multi-effect evaporators and crystallised. Not all sucrose is crystallised in this process, and the residual sugar-rich solution, known as molasses, may be reprocessed to extract additional sugar. The final molasses, which does not return to the sugar production process, contains some sucrose along with high levels of fermentable sugars (such as glucose and fructose, resulting from the breakdown of sucrose). This molasses can be used as a raw material for bioethanol production via fermentation.

FIGURE 20. Processes for producing sugar and bioethanol from sugarcane



Source: Brito Cruz *et al*. (2012).

Thus, bioethanol production from sugarcane can rely on the fermentation of either straight cane juice or a mixture of juice and molasses, as is most commonly practised in Brazil. When producing bioethanol from direct juice, the initial stages—from cane reception to the preliminary treatment of the juice—are similar to the sugar production process. For more complete treatment, the juice undergoes liming, heating, and decantation, similar to sugar processing. After treatment, the juice may be evaporated to adjust its sugar concentration and eventually mixed with molasses, resulting in a mash—a sugar-rich, sterile solution ready for fermentation.

The mash is transferred to fermentation tanks, where yeast (single-celled fungi of the species *Saccharomyces cerevisiae*) is added. The fermentation process takes 8 to 12 hours. During this time, the sucrose and other sugars (hexoses, such as glucose and fructose) present in the mash are converted into carbon dioxide and bioethanol, producing wine (fermented must with an alcohol concentration of 7% to 10%).

The conversion of sucrose into simpler sugars (a process known as sucrose inversion into hexoses, catalysed by enzymes), and their subsequent conversion into ethanol and carbon dioxide, can be represented by the following chemical reaction:

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 2\ C_6H_{12}O_6 \rightarrow 4\ C_2H_6O + 4\ CO_2 \qquad (4)$$

According to this equation, in theoretical terms, 1 kg of sucrose produces 1.0526 kg of hexoses, which in turn yield 566.3 g of pure ethanol (absolute). Given the density of pure ethanol (0.7893 kg/litre), the following theoretical yields can be estimated:

- 1 kg of sucrose produces 0.647 litres of pure ethanol
- 1 kg of reducing sugars (hexoses) produces 0.684 litres of pure ethanol

The most commonly used fermentation process in Brazilian distilleries is the Melle-Boinot process, which is characterised by the recovery of yeast from the fermented "wine" (the liquid resulting from fermentation) via centrifugation. After fermentation, the yeast is recovered and treated for reuse, whilst the wine is sent to the fractioning columns.

During the distillation process, bioethanol is initially recovered in its hydrated form, with approximately 96° GL (96% ethanol by volume), corresponding to around 6% water by weight. The residual by-product from this process is vinasse, produced in a ratio of 10 to 13 litres for every litre of hydrous bioethanol. Other liquid fractions are also separated during distillation, yielding secondary alcohols and fusel oil, a mixture of higher alcohols, such as amyl, isoamyl, butyl and propyl. The hydrous bioethanol can either be sold as the final product or further dehydrated to produce anhydrous bioethanol, which is blended with gasoline.

As ethanol and water form an azeotropic mixture at 95.5% ethanol and 4.5% water, their components cannot be separated by simple distillation. Currently, three methods are used to reduce the water content of hydrous ethanol: (a) dehydration with cyclohexane, which forms an azeotrope with water at a lower temperature, allowing the water to be separated by distillation; (b) dehydration with monoethylene glycol, which absorbs water in the liquid phase, releasing ethanol as vapour; (c) dehydration using molecular sieves, with zeolites that have a high capacity for water adsorption and can be regenerated. Adsorption is the process by which molecules are retained on the surface of materials.

Despite the higher initial investment required, due to the lower energy and water consumption, and in response to increasing international market demands, bioethanol producers are increasingly opting for molecular sieves, which are capable of producing cheaper, contaminant-free anhydrous bioethanol.

The flexibility to use sugarcane sugars either wholly or partially for the production of bioethanol offers an important advantage to this agroindustry. Based on market conditions, prices, and demand, producers can adjust their production strategies to minimise costs and maximise economic benefits. To take advantage of this flexibility, many Brazilian mills have production lines for both sugar and bioethanol, each capable of processing around 75% of the juice extracted. This allows them to operate at about 50% of their total production capacity in relation to the extraction capacity of the mills.

Table 5 provides a summary of the key parameters for sugarcane cultivation and processing in the Centre-South region of Brazil. The two frequently used parameters in the sugarcane agroindustry are:

- POL: This indicates the apparent sucrose content in the sugarcane juice. The higher the POL % value, the better the industrial quality of the raw material.
- TRS: This refers to the total recoverable sugars, representing the total sugars in the sugarcane (measured as glucose) that can be converted into ethanol. These sugars primarily include glucose, fructose, and sucrose. When sucrose breaks down into hexoses, 1.0 kg of sucrose absorbs water and produces 1.053 kg of hexoses.

TABLE 5. Reference values for the sugarcane agroindustry in the Centre-South region of Brazil

INDICATOR	VALUE
Productivity	
Productivity in sugarcane (2023/2024 harvest)	88.2 tc/ha*
Productivity in total sugars (TRS)	139.2 kg TRS/tc
Productivity in energy (sugar + fibre)	7,200 MJ/tc (1.2 boe/tc)**
Average sucrose content (POL % cane)	14.2%
Average fibre content (bagasse % cane)	12.7%
Average agro-industrial productivity	7,500 litres ethanol/ha
Fertiliser use (varies by production environment, variety, and age of the sugarcane field)	
Nitrogen	
Plant cane	30 to 60 kg/ha
Ratoon cane with vinasse	Optional
Ratoon cane without vinasse	80 to 150 kg/ha
Phosphorus (as P_2O_5)	
Plant cane	100 to 150 kg/ha
Potassium (as K_2O)	
Plant cane	100 to 150 kg/ha
Ratoon cane with vinasse	Optional
Ratoon cane without vinasse	100 to 150 kg/ha
Lime	1.9 t/ha (only during planting)
Filter cake application	5 t (dry basis)/ha
Vinasse application	Up to140 m^3/ha

*tc/ha = tonne of cane per hectare
**boe/tc = barrel of oil equivalent per tonne of cane

Source: Prepared by the authors based on Macedo (2006); CGEE (2012) and Embrapa (2022a).

3.1.6. Recent improvements in sugarcane processing

The technologies used in the industrial processing of sugarcane underwent remarkable advancements from 1980 to 2005, reaching very high efficiency levels, as shown in Table 6. Since then, with some exceptions, performance improvements in equipment and processes have become more challenging and less intense. This relatively stable scenario has been influenced by the decreased economic attractiveness of this agro-industry, which in turn has reduced its propensity for innovation.

TABLE 6. Process efficiency of sugarcane bioethanol production in Brazil

PROCESS	1975	2005	(ESTIMATED IN 2012) 2015	2025
Cane washing efficiency (%)	-	99.3	99.7	99.99
Juice extraction efficiency (%)	93	96.1	96.4	98.00
Juice treatment efficiency (%)	98	99.5	99.6	99.75
Fermentation efficiency (%)	80	91.1	90.5	92.00
Distillation efficiency (%)	-	98.0	99.8	99.75

Source: Prepared by the authors based on Nogueira and Leal (2012).

Among the exceptions mentioned above, three innovations in sugarcane processing for bioethanol production stand out, having been progressively introduced into mills over recent decades with positive results: the electrification of mills, the adoption of digital control systems, and efficiency gains in fermentation.

The electrification of mills, choppers, and shredders, employing three-phase induction motors controlled by high-efficiency frequency converters powered at medium voltage, has replaced conventional steam turbine drives, offering various advantages. In addition to the estimated energy savings of around 12% (Chicoa, 2017), these drive systems have improved productivity via better control of the milling process, flexibility in adjusting the mill's speed, smooth starting and stopping, and remote operation, which reduces the risk of accidents.

The adoption of modern measurement, control, and automation systems in sugar and ethanol mills has represented a significant leap in productivity and product quality. By implementing practices already established in other industries, such as paper and pulp manufacturing, various technologies using remote connection resources have been introduced over recent decades, allowing operations within the mill to be conducted with reduced time and cost. For example, supervision and control systems for steam and electricity production have been established, enabling real-time monitoring of production processes from sugarcane preparation via distillation and dehydration.

Control and automation techniques have evolved significantly since the early process computers of the 1970s to today's Process Information Management Systems (PIMS) and Control Loop Management, integrating various supervisory systems with production processes. This so-called digital transformation of the sugar-alcohol industry has required the installation of instruments for measuring physical parameters, data communication networks, and actuation and automation systems within the production environment.

FIGURE 21. Steam generation management system in sugarcane mills

Photo: Lucas de Araújo/WEG.

In addition to a forward-thinking approach, this new context has required staff training and development, as well as a learning period to ensure adequate utilisation of the available capacity—activities that are still ongoing at many plants. Nevertheless, this is a path of no return; modern mills today differ significantly from those of the late twentieth century, boasting a high level of efficiency in processes, product quality, energy rationality, and, above all, economic viability, with reduced operational costs and improved utilisation of installed capacity.

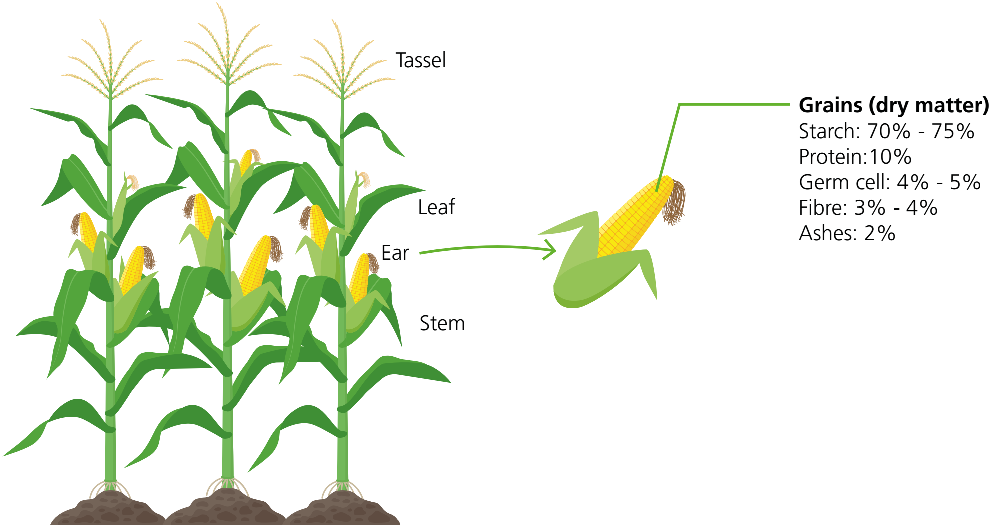
The third significant innovation in the production process of sugarcane ethanol relates to fermentation, in which substantial gains in efficiency have been achieved in recent decades, enabling the production of 90 litres of ethanol per tonne of cane. Alongside the contributions of the aforementioned process control systems—which focus on temperature, pH, and sterility to promote improvements in fermentation yield over time and sugar conversion—the careful selection of yeast strains capable of remaining productive at higher ethanol concentrations has also been crucial. Attention has also been given to the nutritional requirements and concentration of stress indicators in yeast (such as glycerol) or toxic substances (sulphites, excess calcium, potassium, or aluminium) (Fermentec, 2024).

The evaluation and forecasting of process efficiencies in bioethanol production, as indicated in Table 6, primarily capture losses of sugars and bioethanol, but do not reflect how energy efficiency in the industrial process has evolved. This is a relevant aspect discussed in Chapter 6, particularly highlighting the significant expansion of cogeneration and the introduction of biodigestion of vinasse and filter cake. Moreover, the table does not provide information on how environmental issues have evolved—these are explored in Chapter 7, which focus on environmental sustainability within this agro-industry. These aspects, as well as the innovative technologies currently under development and in initial implementation within the sugar and alcohol industry, will be addressed in subsequent chapters.

3.2. Maize bioethanol

Similar to sugarcane, maize (*Zea mays spp.*) is a C4 plant belonging to the grass family, with an annual production cycle. Originating from Mexico, it was domesticated approximately ten thousand years ago from primitive varieties during the early stages of agricultural activities. Today, maize is one of the most important cereals for humanity, and its name, derived from Indigenous Caribbean languages, means “sustenance of life.”

FIGURE 22. Typical composition of maize biomass



Source: Adapted from Seabra (2008).

Today, maize is cultivated on all continents, covering approximately 203 million hectares (FAO, 2024), about eight times more than sugarcane. In the 2023/2024 season, around 1.23 billion tonnes of maize were produced (USDA, 2024). It constitutes a major component of the food supply in various countries, serving as a source of nutrition for both humans and animals. Additionally, maize is a key raw material for a wide array of products, including energy, particularly in countries such as the United States, Brazil, and Argentina.

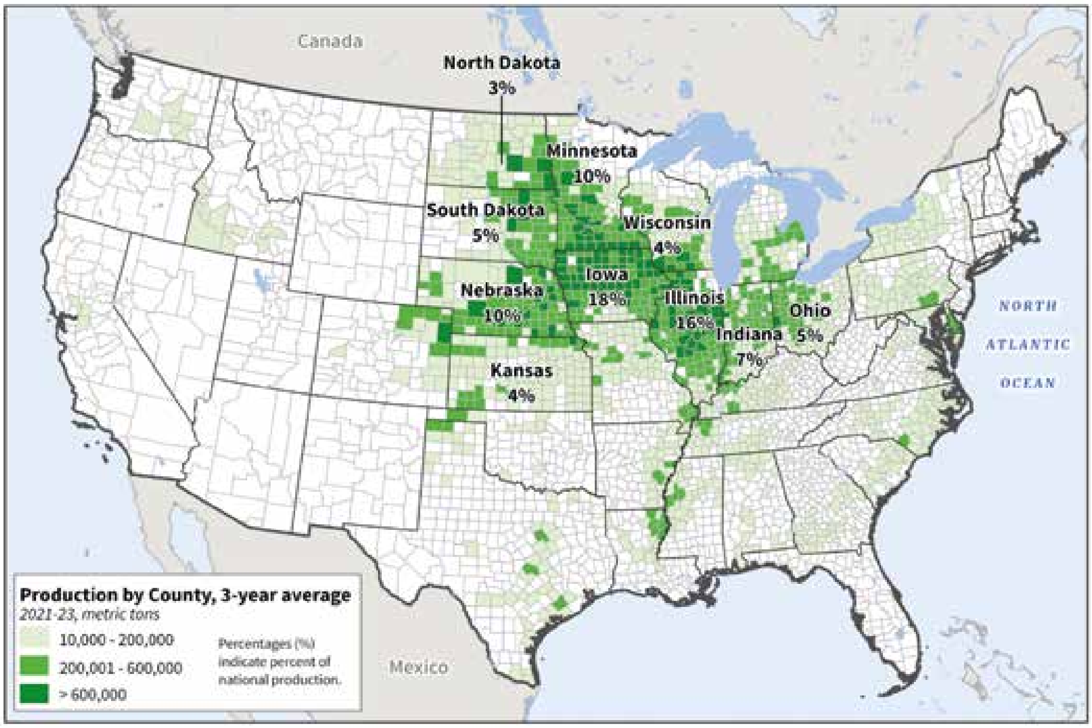
3.2.1. Maize production in the United States

The United States is the largest producer of ethanol globally, accounting for 54% of the world's supply, with maize constituting 93.5% of the raw material used for producing this biofuel (Li *et al.*, 2022). The remainder is derived from cellulosic biomass (4.1%), sorghum (2.2%), and food waste (0.2%). The US leads the world in maize production, contributing 32% of the total maize output. In the 2023/2024 season, American production reached approximately 390 million tonnes of maize, harvested from an area of 36 million hectares, resulting in an average yield of 10.8 tonnes per hectare (USDA, 2024).

Of the total maize produced, 39% was allocated for animal feed, whilst the ethanol industry consumed 37% of US maize produced in 2023 (AFDC, 2024).

Within the US, maize production is concentrated in a region known as the Corn Belt, with particular prominence in the states of Iowa, Illinois, and Nebraska, which together account for 44% of the national production, as illustrated in Figure 23.

FIGURE 23. Maize production in the United States (average 2021–2023)



Source: USDA (2024).

Due to its intolerance to cold, maize is planted in temperate zones during the spring months, typically April and May in the Northern Hemisphere (USDA, 2024), with a single crop produced annually.

3.2.2. Maize production in Brazil

In Brazil, maize cultivation has a long history, primarily used for human and animal consumption since colonial times. For many years, the successful production of sugarcane ethanol limited interest in maize as a feedstock for biofuel. However, this scenario began to shift in 2012 with Usimat's pioneering production of maize ethanol in Mato Grosso during the sugarcane off-season. This opportunity expanded and consolidated five years later with the opening of FS Bioenergia, the first Brazilian plant exclusively producing maize-based ethanol. Today, maize ethanol accounts for approximately 20% of Brazil's ethanol production and continues to grow.

Local conditions, particularly the expansion of maize production in recent years, have driven the growth of maize-based ethanol. In favourable climates, maize is cultivated in a multi-cropping scheme, following the harvest of a nitrogen-fixing crop, typically soybeans, which reduces the need for fertilisers. This region also has access to planted wood used as fuel for the ethanol production process.

The practice of sequentially planting soybeans and maize on the same land has yielded impressive results, with the second harvest now accounting for more than 75% of Brazil's maize production in recent years. This intensification of agricultural production was not fully captured in land use statistics until recently, when EMBRAPA and the FAO updated land use models, re-evaluating agricultural land use based on official statistics (EMBRAPA, 2022c).

A key finding was the recognition that the harvested area could exceed the cultivated area, and that the cropping frequency, calculated by dividing the harvested area by the occupied area, provides insight into land use efficiency. In Brazil, previous estimates suggested values below 1; with updated data, the cropping frequency now exceeds 1.2, which is 30% higher than current estimates in the literature and the global average. This means that climatic conditions enable increased production without expanding land use.

These conditions are especially relevant to Brazil's central-west region, which accounts for 99.5% of the country's maize ethanol production. Almost all maize produced (97%) is a second crop, planted after soybeans in the same area during the same agricultural cycle. In essence, soybeans and maize are both planted and harvested within the same year, on the same plot of land.

In the 2023/2024 harvest, 21 million hectares were planted with maize in Brazil, 78% of which was a second crop. The estimated production is 115.7 million tonnes, with an average yield of 5.49 tonnes per hectare, slightly higher in the central-west due to advanced agronomic technology. The significant difference between Brazilian and US maize yields is primarily due to the higher use of fertilisers in the US.

FIGURE 24. Maize harvest in Mato Grosso, Brazil

Photo: Leonardo Oka/FS Fueling Sustainability.

This method of increasing biomass production without expanding cultivated land, which sometimes includes a third crop in a year, has potential for further growth. A study by EMBRAPA, using data from maize and soybean planting areas combined with agricultural zoning information from the Brazilian Ministry of Agriculture, estimated that 11.8 million hectares of agricultural land have the climatic potential for expanding second-crop maize production in Brazil via the soybean-maize succession system. Most of this land is in the Central-West, and western Paraná, Minas Gerais, and São Paulo. Planting these additional areas could lead to a 2.18-fold increase in maize production during the second harvest season (EMBRAPA, 2015).

3.2.3. Maize ethanol production

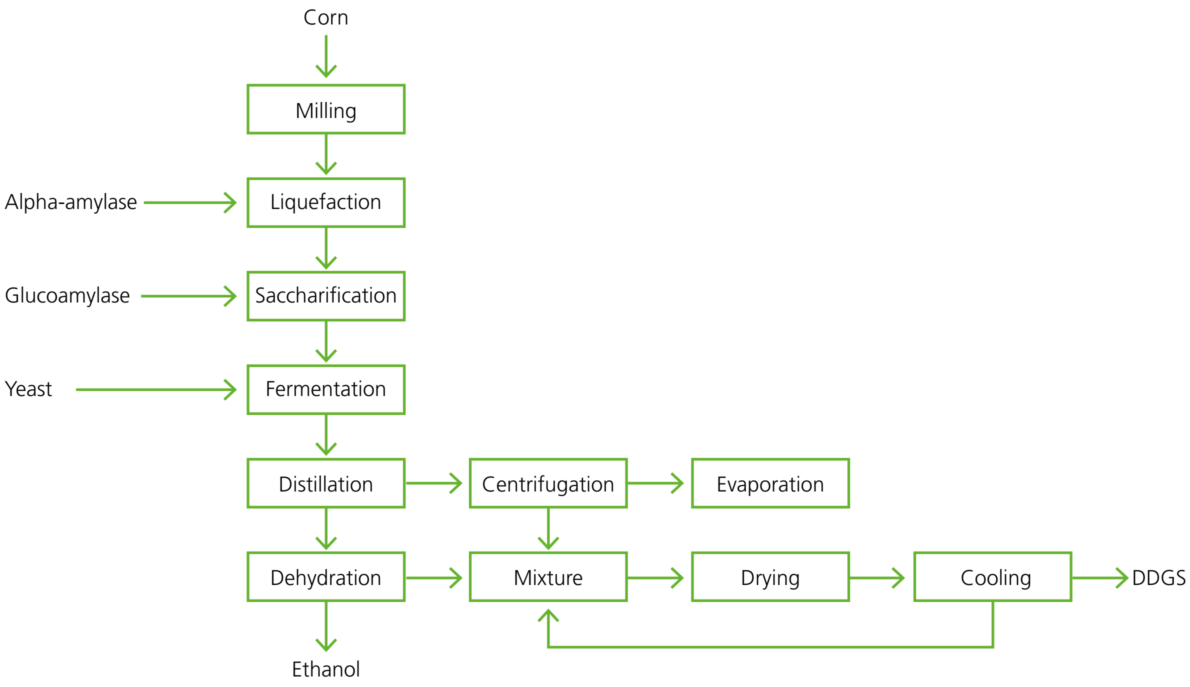
Maize ethanol can be produced via two processes: wet milling or dry milling. Wet milling was the most commonly used method until the 1990s, but dry milling, being simpler and having lower investment and operating costs, has since become the dominant process. Nowadays, around 90% of ethanol production in the United States uses the dry milling method, which is also adopted by

Brazilian plants. The main differences between these two processes lie in the initial treatment of the grain and the by-products obtained.

Dry milling process

Figure 25 outlines the main stages of the dry milling process. At the plant, maize grains are weighed, their quality is assessed, and they are cleaned before being sent for milling.

FIGURE 25. Dry milling process for maize ethanol production



Source: Prepared by the authors based on Wyman (1996).

Using hammer or roller mills, the grains are ground into particles, increasing their surface area to accelerate subsequent processes. The ground maize is then mixed with water to form a paste, which is heated to create a viscous suspension of starch. Under the action of the enzyme alpha-amylase, this starch is liquefied, breaking down the starch chains. In the next stage, saccharification, these chains are further broken down into fermentable hexoses by gluco-amylase enzymes, which are then sent for fermentation, as in the sugarcane ethanol process.

The liquefaction and saccharification stages require different optimal conditions in terms of temperature and pH, so they must be carried out in separate reactors. However, saccharification and fermentation can be combined in one step, known as simultaneous saccharification and fermentation (SSF), in which the enzyme and yeast are added to the same reactor. Although this requires greater process control, SSF can reduce capital costs and save time (Clifford, 2018). After fermentation, the distillation and dehydration of the bioethanol follow a similar process to that used in sugarcane-based plants, but with an important difference regarding the process effluents.

In the dry milling process, after ethanol is extracted from the fermented liquid, the distillery effluent is centrifuged to separate the solid fraction, which then is dried, and the liquid fraction, which is concentrated by evaporation. These fractions are valuable by-products, marketed in two ways:

- DDG (dried distillers grains): This is the dried solid fraction of the distillery effluent, used as animal feed, and rich in protein and fibre.
- DDGS (dried distillers grains with solubles): Similar to DDG, but also includes soluble residues from fermentation, which are dried together with the DDG. DDGS is even richer in protein and energy than DDG.

FIGURE 26. By-products of maize ethanol production used for animal feed (DDG and DDGS)

Photo: FS Fueling Sustainability.

As reference values for the dry milling process, Wang *et al.* (2023) presents the following yields per 1,000 kg of maize:

- 426 litres of anhydrous bioethanol
- 166 kg of wet DDGS
- 69 kg of dry DDGS
- 13.8 kg of crude maize oil

Using this process, and considering respective agricultural productivities, 2,550 litres of bioethanol can be produced per hectare in Brazil's Central-West region, and 4,600 litres per hectare in the United States.

Wet milling process

The wet milling process, though more complex and costly than dry milling, stands out for the variety of valuable by-products it produces and the absence of dried distillers grains (DDG). In wet milling, before the grain is ground to separate its basic components, it is soaked in water. Milling begins with a slight maceration of the maize, allowing the germ, oil, gluten, and fibre to be recovered and processed separately from the starch. The gluten (protein) component is filtered and dried for use as animal feed. The remaining starch can then be fermented to produce bioethanol, using a process similar to that of dry milling, with liquefaction and saccharification steps preceding fermentation.

The removal of solids before hydrolysis and fermentation makes the distillation process simpler and more energy efficient. As this process produces a higher volume of starch, yields are around 440 litres of bioethanol per tonne of maize. Wet milling plants primarily produce corn sweeteners alongside bioethanol and other by-products such as maize oil and starch (AFDC, 2024).

3.3. Bioethanol from other raw materials

Besides sugarcane and maize, other crops also offer raw materials with sugar or starch content that can be converted into bioethanol. In some countries, crops like cassava, wheat, and sugar beet are utilised, and the potential of sweet sorghum is often mentioned. These alternatives are briefly discussed below.

Cassava

Cassava (*Manihot esculenta*) is a plant native to Brazil, with starchy tubers, widely cultivated in tropical regions of Africa and Asia. Brazil is the fifth largest producer in the world, behind Nigeria, the Democratic Republic of Congo, Thailand, and Ghana (FAO, 2024). In addition to its extensive use as a staple food in both human and animal diets, cassava starch (as tapioca) is produced in some countries for export and used locally to produce bioethanol for beverages. Its main advantages include a high starch content in its roots, from 20% to 30%, along with its hardy cultivation, low environmental requirements, and the capacity to be produced almost year-round.

These characteristics motivated early efforts to use cassava during the first phase of Proálcool, Brazil's bioethanol programme, in the 1970s. However, these projects did not progress due to the higher cost of cassava bioethanol compared to sugarcane bioethanol, as well as the irregular root supply to industry.

Today, cassava has been used for several years to produce fuel bioethanol in Thailand. In 2021, 3.3 million tonnes of cassava were processed to produce 530 million litres of bioethanol, about 36% of the country's total production of this biofuel, supplemented by sugarcane bioethanol (juice and molasses), aiming to meet a 12% ethanol blend mandate in all gasoline consumed in the country (USDA, 2022).

For bioethanol production, cassava roots are peeled, washed, and ground, then passed to cookers and, subsequently, to tanks for starch saccharification. In cassava processing, acid hydrolysis is more commonly used than the enzymatic process typically applied to grains. With industrial productivity levels similar to maize, one tonne of fresh cassava with around 25% starch content can produce 170 litres of bioethanol. Cassava's agricultural yield varies considerably, reaching 70 tonnes per hectare in the best conditions, but considering the average yield in well-managed Brazilian plantations, around 18 tonnes per hectare (EMBRAPA, 2024d), this results in an agro-industrial productivity of 3,060 litres of bioethanol per hectare.

Grains, especially wheat

In addition to maize, various starchy grains like wheat, rice, barley, and rye—particularly those of lower food quality and during periods of low prices, have been used on a smaller scale for bioethanol production. Wheat (*Triticum spp.*) has been widely used in recent years in European countries such as Germany and France, competing with locally produced or imported maize. Both cereals undergo similar industrial processes for bioethanol production, with the choice driven primarily by price and availability. Bioethanol production in European countries in recent years has been around 5.3 billion litres, to meet 10% ethanol blending mandates in gasoline (USDA, 2024).

For wheat, adopting the average agricultural yield in Europe (FAO, 2024) and the standard industrial productivity for this raw material (Patni *et al.*, 2013)—4.40 tonnes per hectare and 390 litres of bioethanol per tonne of processed grain, respectively—the agro-industrial yield comes to 7,550 litres of bioethanol per cultivated hectare. Moreover, similar to maize, about 320 kg of valuable animal feed by-products are produced per tonne of wheat processed.

Sugar beet

Among crops that directly produce sugar—apart from sugarcane—sugar beet (*Beta Vulgaris* L. *var. saccharifera*) has been used particularly in Europe to manufacture bioethanol, often using residual molasses available from industrial sugar production. The tuberous root accumulates high amounts of sugar, with yields between 60 and 80 tonnes per hectare and sucrose levels of around 18%, enabling the production from 90 to 100 litres of bioethanol per tonne, with an agro-industrial productivity of about 6,650 litres of bioethanol per hectare (Mall *et al.*, 2021).

Industrial processing of sugar beet begins with cleaning and slicing the beet into thin strips, which are then passed through a diffuser, in which they are washed with hot water to extract the sugar. The resulting liquid contains about 16% soluble solids extracted from the sugar beet and is processed similarly to sugarcane juice, for either sugar or bioethanol. The solid residue from the diffuser is a fibrous pulp that can be used as animal feed, with about 50 kg produced per tonne of processed beet. Despite its high productivity, sugar beet requires external energy (electricity and fuel) for processing.

Sorghum

Sorghum (*Sorghum bicolor*), a grass native to Africa, is the fifth most produced cereal in the world—after wheat, rice, maize, and barley—and is widely cultivated for food across countries in Africa, Asia, and Central America

(FAO, 2024). With its C4 photosynthetic mechanism, sorghum has a high capacity for converting solar energy into biomass and demonstrates good resistance to water stress, heat, and high solar radiation. These traits make it suitable for cultivation with minimal technological input in conditions that are suboptimal for other crops (EMBRAPA, 2013).

These characteristics justify growing interest in sorghum—both in its grain and sweet varieties—for bioenergy production. As a result, despite its relatively lower productivity compared to traditional crops, sorghum is increasingly being considered, particularly as a complement to sugarcane production, aiding to reduce industrial downtime during the sugarcane off-season. In recent years, sorghum cultivation in Brazil has grown significantly, with some mills indicating plans to process it for bioethanol production.

3.3.1. On new routes, technologies and raw materials for ethanol

When selecting a crop as a raw material for bioethanol production, it is essential to consider broad efficiency criteria. This means prioritising crops that minimise the need for land, water, and external inputs such as agrochemicals, among other factors. This assessment should encompass the entire process, from field to wheel—that is, from agricultural production to the logistics of delivering raw materials to the industry and, ultimately, to the point of consumption.

Equally important is the economic viability of the chosen crop. It makes little sense to propose using high-value or premium crops for bioenergy production. Typically, the raw material accounts for 60% to 70% of the final bioethanol cost, so finding low-cost alternatives is crucial. The existence of co-products and by-products, whether for food, industrial, or energy use, is also significant, as it offers desirable flexibility in bioenergy production by linking biofuel availability to other sources of economic value.

Another critical factor in selecting biomass for bioethanol production is its energy balance—specifically, the ratio of energy produced to the direct and indirect energy required to generate it. High-yield crops with low external energy input are more attractive. This point is addressed in Chapter 7, which discusses biofuel sustainability.

This chapter reviewed conventional technologies for bioethanol production that are already implemented in many countries. The next chapter, focused on advanced bioenergy and biomaterials technologies, will discuss innovative bioethanol production methods, particularly those based on the hydrolysis of cellulosic materials.

4.

Advanced technologies in bioenergy and biomaterials production

Innovation opportunities do not come with the tempest but with the rustling of the breeze.

Peter Drucker

Sustainable bioethanol production, enabling the efficient use of known and widely cultivated raw materials, as presented in the previous chapter, has stimulated the development of various downstream and upstream technologies in the agro-industrial process. In this context, new raw materials have been introduced, and the range of products has expanded and diversified. This chapter focuses on technologies that are still under development or at early stages of adoption by the bioenergy agroindustry, to be considered in the various contexts in which bioethanol production has been implemented. To this end, the following topics are presented:

- Energy cane, developed from the recovery of characteristics of primitive cane species, with high fibre content, high productivity, and an energy value superior to that of conventional sugarcane.
- Second-generation ethanol production processes, using lignocellulosic material from cane (bagasse and cane straw) as feedstock, with mills already in commercial operation.
- Various biomaterials that can be obtained from bioethanol, some already commercially produced, such as butadiene (synthetic rubber), and others currently being produced with promising results, such as green polyethylene.
- The use of bioethanol as fuel in stationary gas turbines, including the results of a long-term validated test.
- The development of sustainable aviation fuels (SAF) from bioethanol, representing one of the promising routes for producing these fuels.
- Carbon capture and use in the bioethanol agro-industry, a process of great interest in the context of tackling global climate change.
- Renewable hydrogen production from bioethanol.

Moreover, Chapter 6 addresses widely adopted technologies such as cogeneration, biogas production from vinasse and filter cake, the harvesting and use of cane straw, and the circularity in maize bioethanol production, with a focus on the Brazilian context.

4.1. Energy cane

Sugarcane variety selection has long focused on maximising photosynthetic efficiency to increase sucrose content and reduce fibre in stalks, aiming to boost sugar production and facilitate milling processes. This predominant breeding paradigm has led to the backcrossing of commercial *Saccharum officinarum* hybrids with low-fibre, high-sugar ancestral species, which, while effective, has reduced plant vigour and limited productivity potential. Under optimal conditions, sugarcane's fresh biomass productivity is estimated to reach up to 400 tonnes per hectare per year (Abril *et al.*, 2024), while the global commercial average remains below 25% of this potential. Despite recent advancements in productivity and varietal diversification, sugarcane's genetic potential still allows for significant additional gains, with direct implications for agroindustrial performance and the development of lignocellulosic biomass processing technologies.

In the 1980s, Alex G. Alexander proposed a paradigm shift from the traditional sugar-focused approach in Puerto Rico, advocating for a comprehensive assessment of fibre content to enhance overall productivity and performance (Matsuoka *et al.*, 2014). His recommendations were part of a broader strategy to revitalise the struggling Puerto Rican sugarcane industry at the time. Alexander and his research team emphasised the importance of utilising the entire sugarcane plant—including juice, fibre, tops, and leaves—derived from the most productive cultivars (Souza Barbosa *et al.*, 2020). This integrative perspective highlighted the potential for maximising resource efficiency and improving the economic viability of sugarcane production by recognising the value of all plant components, rather than solely focusing on sugar extraction.

Within this framework, which has become increasingly viable following advancements in sugarcane genetics, energy cane is defined as a variety characterised by lower sucrose content and higher fibre content compared to traditional sugarcane cultivars. More importantly, energy cane demonstrates significantly higher yields in terms of tonnes of biomass per hectare. Modern commercial sugarcane hybrids primarily result from interspecific crosses between *Saccharum officinarum* and *Saccharum spontaneum*, with limited contributions from other *Saccharum* species. Recent advances in the hybridisation of commercial sugarcane with wild variants demonstrate significant potential for developing energy cane varieties, which are beginning to enter the market (Abril *et al.*, 2024).

Prominent Brazilian breeding programmes, including Sugarcane Technology Centre (CTC), Agronomic Institute of Campinas (IAC) and Interuniversity Network for the Development of the Sugar Energy Sector (RIDESA), involving several universities, are actively focused on cultivating these high-yielding energy cane cultivars. Their efforts aim to enhance biomass production and improve overall agroindustrial efficiency, thereby contributing to the sustainability and productivity of the sugarcane sector. Notably, the IAC, in partnership with GranBio, is working on a set of clones that exhibit approximately 50% greater biomass production compared to conventional sugarcane (Sica *et al.*, 2023).

To exemplify the difference between conventional and energy cane, Table 7 presents specific characteristics of sugarcane and energy cane. Due to its high energy productivity, energy cane offers potential advantages, increasing greenhouse gas mitigation and the efficient atmospheric carbon conversion into biomass. Additionally, it exhibits greater resilience to biotic and abiotic stressors and requires less land for a given amount of energy production (Boschiero *et al.*, 2023). Unlike conventional sugarcane, which requires precise timing for optimal sugar production, energy cane does not depend on specific harvest periods, enhancing flexibility and operational efficiency (Santos *et al.*, 2020). Nevertheless, it should be considered that the high fibre content in energy cane typically requires adaptation of harvesting and processing equipment, as well as appropriate management schemes to deal with the increase of solid material in the mill.

TABLE 7. Comparison of commercial sugarcane hybrids and energy cane clones

CHARACTERISTIC	COMMERCIAL (RB72454)	ENERGY CANE (CLONE)
POL % cane	14.60	8.74
Fibre % cane	12.05	19.80
Stalks t/ha	148	155
Fibre t/ha	17.08	30.63

Source: Prepared by the authors based on Santos *et al.* (2020).

Energy cane cultivars are generally taller, reaching heights of up to 6 metres, and thinner, with diameters ranging from 1.5 to 2 cm, compared to commercial sugarcane hybrids (Boschiero *et al.*, 2023). These cultivars typically feature narrower leaf blades and produce a significant number of tillers. They exhibit remarkable adaptability to poor soil conditions while maintaining a notable sugar yield per tonne of cane. Currently, these varieties are undergoing evaluation to identify the most suitable cultivars for various production contexts, while also assessing nutritional aspects, responses to pests and diseases, harvesting techniques, and longevity.

Energy cane varieties are characterised by highly developed root systems that play an essential role in promoting strong sprouting and extended plant longevity, thus supporting increased biomass yield. Roots are crucial during the initial development stages, providing water and nutrients necessary for growth until the setts' nutrient reserves are fully expended (Grassi & Pereira, 2019). The large root volume observed in energy cane—about 65% greater than that of sugarcane—contributes to efficient nutrient absorption, enabling multiple successive harvests from a single planting cycle, which enhances the economic viability of biomass production (Abril *et al.*, 2024).

FIGURE 27. Sugarcane and energy cane cultivars

Photo: Gonçalo A. Guimarães Pereira.

TABLE 8. Typical composition of sugarcane and energy cane cultivars

CANE STEM CONTENT	SUGARCANE	ENERGY CANE	
		1G AND 2G ETHANOL	BIOELECTRICITY
Sucrose	> 15%	> 15%	< 15%
Fibre	< 15%	> 18%	> 28%

Source: Prepared by the authors based on Souza (2024).

The advancement of sugarcane varieties with enhanced energy yields, characterised by increased fibre content, is inherently complementary to the development of processes aimed at optimising lignocellulosic raw materials, discussed in the next section. However, it is essential to recognise that energy cane presents a new context involving innovative processes, technologies, resources, and processing challenges. Thus, the introduction of energy cane in the sugarcane agroindustry will likely be progressive, beginning with varieties that show increased fibre levels that remain compatible with current processing systems, while improvements are introduced to handle a more fibrous feedstock.

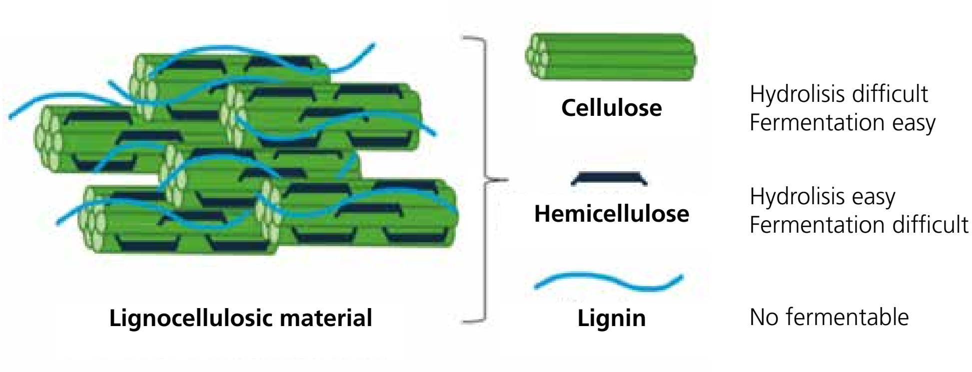
In fact, four decades ago, the pioneering work of Alexander advocated for the inclusion of ethanol production within the sugarcane agroindustry, asserting that the term "energy cane" should not be limited to individual plants but should encompass a holistic management system (Matsuoka *et al.*, 2014). This approach has since been integrated into various breeding programmes worldwide, including those in Australia, Puerto Rico, Barbados, India, Taiwan, Louisiana, and Hawaii (Souza Barbosa *et al.*, 2020). This shift in focus highlights the increasing recognition of biomass production as a critical component of sugarcane cultivation, reflecting the industry's adaptation to meet the growing demand for renewable energy sources.

4.2. Bioethanol from lignocellulosic biomass

Most of the biomass content in sugarcane and other high yield crops consists of insoluble materials: cellulose, hemicellulose, and lignin, which are called lignocellulosic material. In particular, cellulose and hemicellulose are polysaccharides, chains of simple sugars: cellulose is a long chain composed solely of glucose (a molecule with six carbons), whereas hemicellulose is a short chain made composed primarily of pentose (a molecule with five carbons) along with other sugars. Both types of sugar can be fermented into ethanol, with a remarkable difference: while glucose fermentation is easy to be carried out, pentose shows challenging process.

The initial operations to obtain bioethanol from lignocellulosic biomass, the so called second-generation or 2G ethanol (E2G), include the preparation of this material, reducing its size and opening the plant cells (by grinding and steam explosion). Then, although other processes can be used, the enzymatic hydrolysis is the preferred method to break the polysaccharides into their components. Again, there is a significant difference: the hydrolysis of cellulose is quite more difficult than that of hemicellulose.

FIGURE 28. Lignocellulosic material components



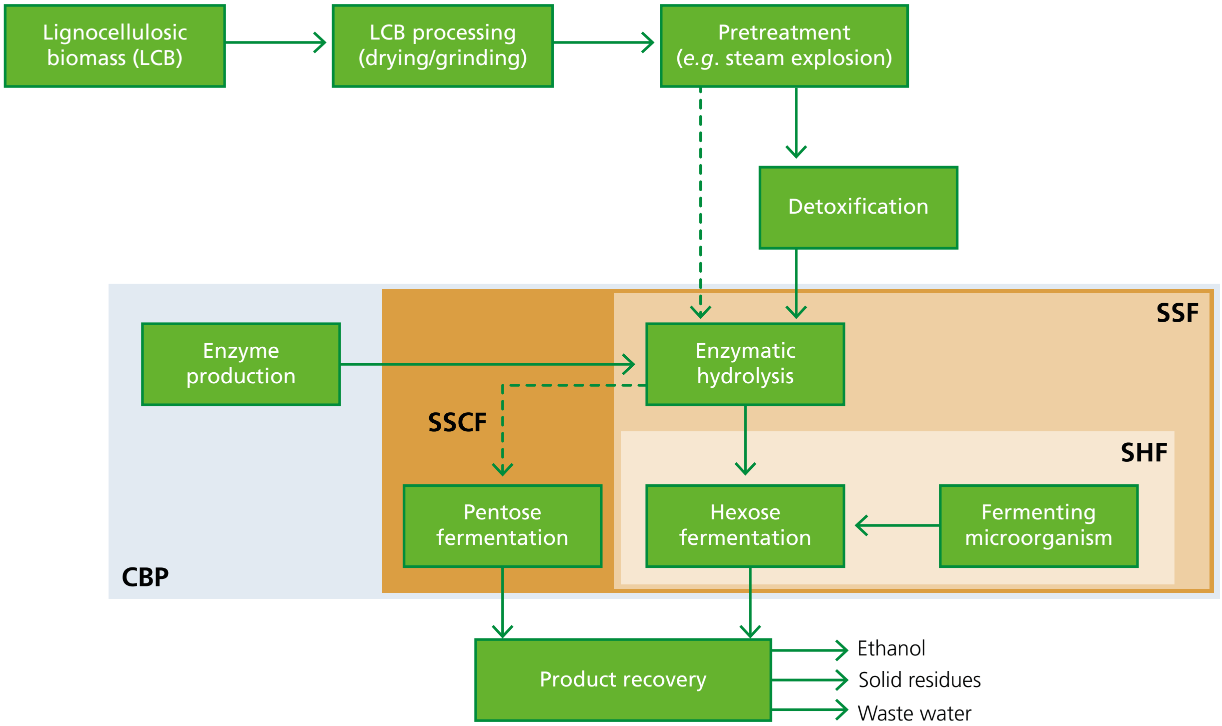
Source: Prepared by the authors.

Thus, although the cellulose and hemicellulose fractions can be effectively converted into ethanol via fermentation, distinct pathways are implemented, either separating or integrating the processes (Milessi *et al.*, 2018). For example, aiming at bioethanol production, enzymatic hydrolysis of cellulose, or saccharification, can occur concurrently with glucose fermentation. This integrated process can be optimised via various configurations, including separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), simultaneous saccharification and co-fermentation (SSCF), and consolidated bioprocessing (CBP) (Aguiar *et al.*, 2021; Brandt *et al.*, 2021; Chandel *et al.*, 2018), as shown in Figure 29.

In the SHF process, the hydrolysis of cellulose and fermentation occur as distinct steps, allowing for the optimisation of each phase. This separation enables enzymes and yeasts to function under their ideal pH and temperature conditions; however, the process is inherently lengthy and complex, requiring additional operational steps (Mesa *et al.*, 2017).

Conversely, the SSF process integrates the hydrolysis and fermentation of released sugars, leading to enhanced ethanol productivity and significant time savings (Diaz *et al.*, 2018). A notable limitation of this method is that the optimal temperature for hydrolytic enzymes (45–50 °C) is substantially higher than that for fermentation (30 °C), which can result in a reduced rate of enzymatic hydrolysis.

FIGURE 29. Routes for biochemical conversion of lignocellulose to ethanol



Source: Adapted from Brandt *et al*. (2021).

To maximise the conversion of released sugars into ethanol and achieve high productivities, the SSCF process employs a blend of yeasts or recombinant yeasts, facilitating the concurrent fermentation of both C6 and C5 sugars (Moraes Rocha *et al*., 2014). Lastly, CBP is a comprehensive technological platform that simultaneously produces enzymes, hydrolyses pretreated biomass, and ferments the liberated sugars (C5 and C6) in a single reactor system, thereby simplifying the overall process. However, this strategy requires the use of microorganisms capable of simultaneously fermenting both C6 and C5 sugars (Batista *et al*., 2019).

The advancement of processes employing lignocellulosic biomass as a feedstock plays a crucial role in promoting sustainability and safeguarding the environment (Vandenberghe *et al*., 2022). Within this framework, recent years have seen considerable interest in the utilization of sugarcane biomass (bagasse and straw) as a raw material for biofuel production. Incorporating sugarcane biomass into biorefineries for second-generation bioethanol production offers the potential to reduce production costs and enhance the sustainability of conventional ethanol production processes (Brown *et al.*, 2024; Dionísio *et al.*, 2021).

4.2.1. Bioethanol production from lignocellulosic biomass in Brazil

In Brazil, the development of demonstration and commercial plants focused on processing lignocellulosic biomass from sugarcane to produce second-generation bioethanol has made considerable progress (EPE, 2024b). Currently, three prominent industrial ventures, operated by GranBio and Raízen, briefly introduced below, have a combined production potential of around 154 million litres of ethanol per year (Granbio, 2024; Raízen, 2024).

GranBio's plant, inaugurated in 2017 in São Miguel, Alagoas, has an annual production capacity of 30 million litres of ethanol, with plans to expand this capacity to 60 million litres by 2026. According to the company, this plant converts sugarcane straw into 2G ethanol (E2G) with the lowest carbon footprint of any biofuel in commercial scale: 8.2 gCO_2e/MJ delivered in Europe (Granbio, 2024).

FIGURE 30. 2G ethanol plant, São Miguel dos Campos, Alagoas, Brazil

Photo: Bernardo Gradin/Granbio.

Raízen, a joint venture between Cosan and Shell, stands out as a global leader in 2G ethanol production, currently operating two plants in São Paulo (SP). The first unit, located at the BioParque Costa Pinto in Piracicaba, SP, began operations in 2014 with an annual production capacity of 40.1 million litres of ethanol. The second facility was inaugurated in May 2024 at the Bonfim Bioenergy Park in Guariba, SP, following an investment of approximately USD 240 million, and has the capacity to produce 82 million litres of ethanol per year (Raízen, 2024).

FIGURE 31. 2G ethanol plant in Bonfim Bioenergy Park, Guariba, SP, Brazil

Photo: Acervo Raízen.

In addition to these operations, Raízen is constructing five new 2G ethanol plants, each with a production capacity of 82 million litres annually, as detailed in Chart 2. The company has also announced plans for two additional projects, with timelines yet to be disclosed, located at the Santa Elisa mill in Sertãozinho, SP, and the Caarapó mill in Caarapó, Mato Grosso do Sul (MS). Raízen's long-term goal is to build twenty 2G ethanol plants by 2030/2031. Through these initiatives, Raízen is a standout company in the sector, being the pioneer and the only company in the world currently commercialising 2G ethanol at scale, achieving a relevant experience in this process (Raízen, 2023).

CHART 2. Raízen's 2G ethanol units and projects

ANNEXED TO THE PLANT	CAPACITY (MILLION LITRES/ YEAR)	SITE	STATUS	START OF OPERATION
Barra	82	Barra Bonita/SP	Under construction	2024/2025
Univalem	82	Valparaíso/SP	Under construction	2024/2025
Gasa	82	Andradina/SP	Under construction	2026/2027
Vale do Rosário	82	Morro Agudo/SP	Under construction	2026/2027
Tarumã	82	Tarumã/SP	Under construction	2026/2027
Santa Elisa	-	Sertãozinho/SP	Project	To be announced
Caarapó	-	Caarapó/MS	Project	To be announced

Source: EPE (2024b).

Despite intensive research in this field, significant obstacles remain to be addressed to enhance process feasibility (Chandel *et al.*, 2021; Buckeridge & Souza, 2017; Kirshner *et al.*, 2022; Maga *et al.*, 2019; Méndez *et al.*, 2021). Key challenges hindering the commercial deployment of second-generation biofuel production include high capital costs, process complexity, and the logistical difficulties associated with mobilising feedstock supplies over extensive catchment areas. These factors have posed significant obstacles to biofuel implementation in regions such as the European Union, Brazil, and the United States.

In less developed countries, where urgent human development needs exist, these challenges are even more pronounced, particularly given that a substantial portion of the world's biomass production potential is concentrated in these regions (Cortez *et al.*, 2018). However, as 2G technologies evolve to become less capital-intensive and complex, there is potential for more rapid deployment, accelerated learning cycles, and improved integration into agricultural landscapes and material flows. This transformation is likely to enhance the economic feasibility of 2G biofuel production on a smaller scale, thereby facilitating its applicability in less developed countries and contributing to sustainable development goals.

As an initiative in this direction, the American startup Terragia Biofuel is at the forefront of biotechnology, developing high-performance industrial microorganisms from nature's most efficient lignocellulose fermenters, with the aim of producing second-generation ethanol and other bioproducts from cellulosic feedstocks. Its innovative approach integrates biological steps into a single operation, eliminating the need for thermochemical pretreatment and the addition of cellulases—factors that represent significant costs in conventional processing paradigms (Lynd, 2024).

As highlighted by Cortez *et al.* (2018), the opportunity for second-generation (2G) biofuels to significantly contribute to climate change mitigation by the middle of this century is narrowing unless deployment rates are substantially increased. Relying on the same strategies utilised over the past decade to achieve this critical objective presents considerable risks. Therefore, a strategic revitalisation, termed "2G 2.0," is required, drawing upon the insights and lessons gleaned from previous experiences in the sector. This renewed approach should prioritise technological advancements, optimise production efficiencies, and enhance the integration of 2G biofuels within existing energy frameworks. By doing so, we can facilitate a more rapid and effective transition towards a sustainable energy future, ultimately ensuring that 2G biofuels fulfil their potential in combating climate change.

4.3. Bioethanol as feedstock for biomaterials production

Synthetic materials, traditionally based on natural gas and petroleum-naphtha, play a key role in our modern life, with a wide range of applications in packaging, the automobile industry, construction, medical products, household items and textiles, whether replacing traditional materials or creating new products.

In this context, bioethanol can also be adopted as feedstock, with advantages over fossil raw materials within the framework of modern Green Chemistry: it is a renewable material, allows for safe processes and products, and presents lower environmental impacts, namely reduced atmospheric carbon emissions and practically no hazardous residues (Matheus & Sousa-Aguiar, 2022).

Ethanol is a homogeneous and reactive substance that can be used as an input in several traditional petrochemical processes, as shown in Chart 3, which in this case could be called alcoholic-chemical processes. Almost all products listed have widespread use in industry, agriculture, and final consumption, with important markets at a global scale.

CHART 3. Basic processes of the alcohol-chemical industry

PROCESSES	MAIN PRODUCTS	TYPICAL APPLICATIONS
Dehydration	Ethylene Propylene Ethylene-glycol	Plastic resins Solvents Ethyl ether Textile fibres
Dehydrogenation Oxygenation	Acetaldehyde	Acetic acid Acetates Dyes
Esterification	Acetates acrylates	Solvents Textile fibres Adhesives
Halogenation	Ethyl chloride	Cooling fluids Medical products Plastic resins
Ammonolysis	Monoethylamine Diethylamine	Insecticide Herbicide
Dehydrogenation Dehydration	Butadiene	Synthetic rubbers

Source: Prepared by the authors based on Schuchardt *et al.* (2001).

Although many of these processes are still at an early stage of development and require specific studies and research on catalysis (Matheus & Sousa-Aguiar, 2022), some routes have already been implemented on an industrial scale. As good examples, two cases of bioethanol-based polymer production in Brazil are presented below: green polyethylene, an expanding initiative implemented in the last decades, and butadiene, a production discontinued after years of success. Both cases offer interesting lessons. A brief comment on biomaterials derived from sugar is also presented.

4.3.1. Ethylene and derivatives

Ethylene is one of the most important building blocks of the petrochemical industry. It can be produced by dehydration of bioethanol and is a precursor to a wide range of second-generation products, such as polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC).

An important global ethylene producer, Braskem has forty units in Brazil, the United States, Germany, and Mexico. In 2001, the company began evaluating the possibility of using renewable feedstocks to produce biopolymers, and in 2007 it proposed a project to use ethanol to produce ethylene, developing its own process at the Braskem Technology and Innovation Centre (CEPAL, 2020).

FIGURE 32. Braskem green ethylene plant in Triunfo, Rio Grande do Sul, Brazil

Photo: Mathias Cramer/Braskem.

After a period dedicated to research and development, in September 2010 Braskem inaugurated a plant in Triunfo, Rio Grande do Sul, and began the production of green PE on an industrial scale, with the first batch being sold in January 2011. This industrial unit received investments of around USD 290 million to process bioethanol and produce 200,000 tonnes/year of green ethylene (CEPAL, 2020). In 2023, with an additional investment of USD 78 million, the capacity of this pioneering plant was expanded to 260,000 tonnes/year (Braskem, 2023a).

In 2022, Braskem announced a partnership with Lummus Technology, a global supplier of process technologies, to license Braskem's technology to produce green ethylene worldwide, aiming to accelerate the use of bioethanol for chemicals and plastics and foster global efforts towards a carbon-neutral circular economy (Braskem, 2023a). Similar agreements have been made with other petrochemical industry players, such as Toyo Engineering from Japan and Neste from Finland. In a joint venture between Braskem and the Thai company SCG Chemicals, a new green PE plant with a capacity of 200,000 tonnes/year is scheduled to be built in Rayong, Thailand, and is planned to be commissioned in 2025. Looking ahead, Braskem has announced the goal of producing one million tonnes of green PE by 2030 and becoming carbon neutral by 2050 (Braskem, 2023b).

Braskem's bioplastic is sold under the "I'm Green" trademark, which appears on final products that use it. The green PE is a drop-in material, meaning it can be used directly in all conventional processing machines and applications, as it is chemically identical to petrochemical PE. The biobased origin of this polymer is regularly certified by the US-based radiocarbon dating laboratory Beta Analytic, confirming that it contains 100% renewable raw material (Braskem, 2024).

To ensure that the bioethanol utilised is properly produced, Braskem developed the Responsible Sourcing Ethanol Programme, which has been in force since 2010, which instils checks and balances into the ethanol supply chain. This programme has two pillars: compliance and excellence, with a Supplier Code of Conduct that establishes "operational standards expected from suppliers in their management of human resources, the environment, local communities, quality, and efficiency" (Braskem, 2024, our translation).

Assuming a conversion efficiency of 95%, 1.73 kg or 2.18 litres of bioethanol are consumed for each kilogram of ethylene produced (BNDES & CGEE, 2008). According to Braskem, based on a life cycle analysis, each kilogram of green polyethylene produced captures and fixes 3.1 kg of CO_2e. In contrast, each kg of petrochemical PE emits 2.1 kg of CO_2, thus about 5.2 kg of CO_2e is saved per kg of green PE produced (Kabe, 2024).

The global ethylene market in 2023 is estimated at 316.8 million tonnes and is expected to reach 406.5 million tonnes by 2030 (Research and Markets, 2024). Based on the above values, using bioethanol to produce 10% of the ethylene required in 2030 would result in an annual demand of about 88.5 billion litres—approximately the current global production of bioethanol—and would mitigate of 211 million tonnes of CO_2 per year, a relevant figure.

The remarkable and successful development of Braskem's green polyethylene project highlights the importance of careful planning, technological mastery of innovative processes, valorisation of the product's unique characteristics and access to the international market.

4.3.2. Butadiene

Based on the dehydrogenation of ethanol into acetaldehyde, it is possible to generate another important group of chemical building blocks: butadiene and polybutadiene, key components of synthetic rubber used in various applications, including tyres.

COPERBO, the Pernambuco Rubber Company, has a long history tying ethanol to the production of chemical inputs. In 1965, the company began operating a butadiene unit in Cabo de Santo Agostinho, Pernambuco, to produce 27,500 tonnes per year of synthetic rubber derived from ethanol, aiming to meet the growing demand for this elastomer, primarily used for tyre production. The process technology adopted by COPERBO was basically from Union Carbide for butadiene and from the Firestone Tire Company for polybutadiene, with local adaptations (Boto, 2021).

In 1971, COPERBO was transferred to Petroquisa, the former petrochemical subsidiary of Petrobras, which provided impetus to increase ethanol use. The inclusion of acetic acid and vinyl acetate in its product line led to the creation of the Brazilian National Alcohol-Chemical Company, in the vicinity of the COPERBO plant (BNDES & CGEE, 2008).

These companies ceased operations in the early 1970s, mainly due to economic difficulties. As the renewable nature of COPERBO's butadiene did not have any advantage in value, and the production of butadiene in petrochemical plants used subsidised naphtha as feedstock, bioethanol became economically unviable.

4.3.3. Other biomaterials based on sugar

Sucrose, the sugarcane component that serves as the precursor of ethanol, also offers several application possibilities in the field of sucrochemistry, providing an accessible, low-priced, ecological, and renewable raw material to produce a wide range of products, generally via biological processes. As an example, since the 1950s and for several decades, at Usina Amália in Santa

Rosa do Viterbo, São Paulo, the company Fermenta produced citric acid from *Aspergillus Niger* cultures in molasses solutions.

Currently, interest in sucrochemistry has grown. Among the most promising intermediate products derived from sucrose are:

- Succinic acid, used in the production of polymers and products in the food, pharmaceutical, textile, and chemical industries.
- Monoethylene glycol (MEG), a raw material for polyethylene terephthalate (PET), which is used in a wide range of applications, including textiles and packaging.

The following paragraphs present innovative processes that remain at the frontier of using sucrose as a raw material to produce biodegradable plastics. These plastics are polymers that, under appropriate environmental conditions, completely decompose within a short period due to microbial action.

Biodegradable bioplastics offer a key advantage: they are produced from renewable sources such as starches, sugars, or fatty acids. An example is polylactic acid (PLA), composed of lactic acid monomers obtained via microbial fermentation, which is currently the most used bioplastic.

Another possibility is to obtain biopolymers directly from micro-organisms as in the case of polyhydroxybutyrate (PHB), polyhydroxyalkanoate (PHA) and their derivatives. In these cases, the biopolymer is biosynthesised as an energy reserve by the micro-organisms themselves. Although the fundamental bioprocess is now well understood, scaling up production units and ensuring economic feasibility remain barriers to large production.

Nevertheless, as an example of implementation in this context, the Usina da Pedra mill launched a pilot plant in 1995 to produce 0.5 tonne/year of biodegradable bioplastics, using batch fermentation processes and sugarcane by-products as feedstock. Based on tests and results from this pioneering venture, the plant was remodelled to produce 50 tonnes/year, improving the process, and a spin-off company, Biocycle, was created to operate a 3,000 tonne/year unit. To produce 2.2 kg of plastic, 6.6 kg of sugar are required, meaning that one hectare of sugarcane can produce approximately 3.6 tonnes of bioplastics per year (Biocycle, 2012).

4.4. Ethanol use in stationary gas turbines

In recent decades, there has been a significant global transition in electricity generation systems towards renewable energy sources, with the predominance of solar and wind power, both in the expansion of installed generation capacity and in the environmentally and economically advantageous replacements of conventional thermal power plants that burn fossil fuels, especially coal and petroleum derivatives. This transition has led to a significant reduction in the carbon footprint of electricity worldwide.

However, solar and wind energy sources are inflexible, vary unpredictably, and cannot be dispatched according to electricity sector demand. With the significant growth of their share in the generation matrix, it has become important to have electricity storage capacity or short-term dispatchable generation to meet demand for stable and reliable operation of electric systems.

In this sense, thermal power generation using biomass, with low fossil carbon emissions, is often an economical and efficient option for increasing electricity supply. This is the case for cogeneration systems that use sugarcane bagasse and straw in plants producing sugar and bioethanol, generating surplus electricity for the public power grid. Recently, these systems have substantially increased their contribution to the Brazilian grid, as presented later in Chapter 6. Nonetheless, cogeneration systems in sugar mills use steam turbines and prioritise the demands for electricity and process heat required to process sugarcane, limiting their capacity to respond to short-term fluctuations in demands of the interconnected utility grid.

Gas turbines (GT), present in most public electricity systems, are appropriate in this context. Aeroderivative gas turbines constitute the most used type of GT for electricity generation worldwide and are of particularly interest. They retain the essential design and key components originally developed for aeronautical applications. However, unlike applications in aircraft that produce thrust, aeroderivative GTs provide mechanical power output for electricity generation. For economic reasons, these stationary GTs typically operate on natural gas instead of liquid aviation fuels such as kerosene or jet fuel. They have the advantage of operating under stable conditions and can burn different fuels in the same unit with minimal modifications—something not feasible in conventional internal combustion engines. These turbines can also operate efficiently with bioethanol, providing excellent performance and reduced emissions, and can respond quickly to dispatch, requiring simplified logistics for fuel supply and storage compared with natural gas.

While aviation fuels must meet strict specifications and biofuels for such applications must be approved by specific standards, stationary GT applications allow for broader fuel options. The primary requirement for these fuels is the cleanliness of combustion products, enabling the use of hydrogen, various process gases, volatile liquid fuels, synthetic fuels, and biofuels (Enagi *et al.*, 2018). This flexibility enhances GTs' advantages in terms of efficiency, reliability, versatility, integration with other thermal systems, and low emissions, solidifying their competitiveness in an era focused on environmental sustainability and fuel cost uncertainties (Garai *et al.*, 2017; GE, 2018).

The global ethanol supply, alongside positive production expansion prospects, availability in regions lacking natural gas, and its low carbon footprint, has spurred studies on its viability for industrial and aeroderivative GTs. Research has focused on the technical aspects of ethanol combustion, particularly within the combustion chamber (Andoga *et al.*, 2021; Carvajal-Mariscal *et al.*, 2013; Garai *et al.*, 2017; Irrazabal *et al.*, 2011; Mendez *et al.*, 2012; Sallevelt *et al.*, 2014).

In 2008, GE Energy and Reliance Energy conducted a comprehensive combustion test at the Goa Power Plant on a GE Frame 6B industrial GT (44 MW nominal output), equipped with standard combustors for naphtha. This test involved naphtha-anhydrous ethanol blends with up to 95% ethanol, revealing that the increased load on fuel pumps, due to the higher flow rate and viscosity of ethanol compared to naphtha, could be mitigated using fuel additives (Alfaro-Ayala *et al.*, 2013). The test was smooth and demonstrated excellent combustion stability, low nitrogen oxide (NO_X) emissions, and nearly zero emissions of carbon monoxide (CO), unburned hydrocarbons, and sulfur dioxide (SO_2). Although detailed information on power output and efficiency was not provided, the lower air/fuel ratio of ethanol suggests that both parameters were likely improved (Moliere *et al.*, 2009).

4.4.1. Data and results of a test of a GT fuelled by ethanol

A more extensive and conclusive test of a gas turbine burning ethanol, in this case replacing natural gas, was conducted at the Juiz de Fora Thermal Power Plant (UTEJF), built and operated by Petrobras, the Brazilian state oil company. Located in Juiz de Fora, Minas Gerais, the plant is equipped with two GE Energy LM 6000 PC gas turbines (each with a nominal output of 43.5 MW), derived from the GE Aviation CF6 turbofan engine, widely used in commercial aircraft. Operating in open cycle, the turbines provide a total installed capacity of 87 MW. Commissioned in 2001 and connected to the Brazilian National Grid, UTEJF was designed to meet peak demand and supplement hydropower generation during the dry season, resulting in an average of 1,100 hours of operation per year during its first decade of service.

FIGURE 33. Juiz de Fora thermal power plant with two GE LM 6000 PC gas turbines operating with hydrous bioethanol

Photo: Geraldo Falcão/Banco de Imagens Petrobras.

The aim of introducing ethanol was to assess the technical feasibility of this change, with the potential to replicate it in other Petrobras GTs as a strategy to mitigate supply risks associated with dependence on Bolivian natural gas at the time. Ethanol offers a valuable alternative fuel, increasing fuel supply security and, consequently, plant reliability during periods when natural gas is unavailable.

FIGURE 34. LM 6000 PC aeroderivative gas turbine and main parameters in power generation version

Power	43.3 MW
Efficiency	41.1 %
Exhaust	454 °C
Speed	3,600 rpm

Source: GE (2019).

The choice of UTEJF considered logistical aspects, such as proximity to major roads and available space to install ethanol reception and storage systems, as the fuel would be supplied by sugarcane mills located approximately 800 km from the plant (Conti, 2011). Initially, one unit was converted from a natural gas-only GT to a dual-fuel configuration, capable of burning hydrous ethanol (94% ethanol by mass), enabling a detailed test under real operational conditions to evaluate emissions, efficiency, and component durability. It was the world's first use of ethanol in a GT for full-scale commercial electricity generation.

The introduction of ethanol as fuel at UTEJF required two main actions: establishing the infrastructure for handling and storing the liquid fuel and modifying the gas turbine to operate with ethanol, which imposes higher fuel flow. The storage infrastructure included a 600 m^3 tank, sufficient for thirty hours of operation at nominal capacity with a consumption rate of 18.4 m^3 per hour. The GT modification involved a series of steps proposed by GE Energy and jointly implemented by Petrobras and GE Energy (Machado, 2010):

a. **Combustion chamber replacement:** The original combustion chamber was replaced with one compatible with liquid fuel, and two out of thirty injector burners were substituted to accommodate ethanol. This was the most complex step, requiring 15 days of work.

b. **Ethanol supply system installation:** An ethanol-specific supply system was installed, including pumps, filters, control valves, piping, instrumentation, and a supervisory system to ensure safe and reliable fuel delivery.

c. **Cooling system installation for the natural gas supply:** A cooling system for the natural gas supply was installed, necessary when only ethanol is being used. Cooling air was extracted from the final stage of the high-pressure compressor.

d. **Demineralised water injection system:** A system for injecting demineralised water into the ethanol was set up to control nitrogen oxide emissions. This required adding a pump, filters, valves, and piping for direct water injection into the air distributor surrounding the combustion chamber.

Adjustments to the control software were also necessary due to the integration of new final control elements for the fuel ethanol system. These modifications were considered relatively straightforward, and following their implementation, the GT was re-tested and recommissioned. An environmental licence and other regulatory approvals were obtained, enabling UTEJF to begin commercial operations with ethanol in December 2009.

Following the modifications, a five-month testing programme was conducted, covering load variation, water injection rates, fuel switching between natural gas and ethanol, operation with dual fuels and ethanol-only, as well as startup and shutdown sequences on ethanol. After 975 hours of operation, which included periodic borescope inspections, the GT was disassembled for a detailed inspection (Machado, 2010).

The results of this test demonstrated that the gas turbine's performance using ethanol was comparable to its performance when operating on natural gas. Emissions of sulfur dioxide (SO_2), aldehydes, carbon monoxide (CO), and unburned hydrocarbons were similarly low, while nitrogen oxides (NO_x) emissions were lower compared to those produced with distillate fuels. Additionally, the wear and tear on hot section components was comparable to operation with distillate fuels over the same operational period. To achieve nominal capacity, a higher mass flow of ethanol was required compared to natural gas; however, due to the lower air-to-fuel ratio of ethanol, the turbine could produce more power per kilogram of air admitted.

Furthermore, the lower calorific value and water content of hydrous ethanol contributed to a decrease in combustion temperature, which in turn reduced NO_x emissions and the need for demineralised water injection for emission control (Machado, 2010). This outcome highlights ethanol's potential as an alternative fuel in gas turbines, supporting lower environmental impact without compromising operational efficiency.

TABLE 9. Main results of GT LM 6000 PC operating with natural gas and hydrous ethanol

PARAMETER	UNIT	NATURAL GAS	HYDROUS ETHANOL	VARIATION (ETH/NG)
Max. power	MW	43,349	43,642	+ 0.67%
Heat rate	kJ/kWh	8,732	8,369	– 4.16%
Efficiency	%	41.2	43.0	+ 4.36%
NO_x emission	ppm	39.8 at 41.2	25.3 at 41.8 39.2 at 41.7	– 36.4% – 1.5%
Water consumption	litre/min	110 at 41.2	106 at 41.8 72 at 41.7	– 3.6% – 34.5%

Source: Machado (2010).

As indicated in Table 9, for approximately the same power output and original water injection rates, nitrogen oxides (NO_x) emissions decreased by about 36% when operating with ethanol. If maintaining the NO_x emission level typical of natural gas operation is acceptable, water injection rates can be reduced by over 34%.

This excellent performance of the GT running on ethanol led Petrobras to convert the second GT unit at UTEJF to a dual-fuel system, a modification completed in 2010. Since then, even with a reliable natural gas supply, the plant has maintained its flex-fuel configuration, keeping both GTs ready to operate on hydrous ethanol—either in combination with or independent of natural gas—whenever required. This flexibility enhances the resilience of UTEJF's energy supply strategy while supporting lower emissions and fuel diversity.

After these successful tests, which confirmed the technical feasibility of using bioethanol to replace natural gas in GT the plant reverted to using this fossil fuel due to economic reasons. However, it maintains the capability to operate using pure hydrous bioethanol or in combination with natural gas whenever it becomes advantageous.

Just as a reference, without considerations on logistics, supply contracts, or the economic impact of carbon emissions, and adjusting for electricity generation efficiency as indicated in the previous table, hydrous bioethanol at USD 0.50/litre is equivalent to natural gas at USD 25/MMBtu. Although this value is high compared to the typical price of USD in the American market (Henry hub), in other markets, such as Asia and Europe, during certain periods, it makes economic sense to substitute natural gas with hydrous ethanol in GTs applied in electricity generation.

4.5. Production of sustainable aviation fuels (SAF) from ethanol

This section is based on a technical note prepared for this book by Rafael Capaz, from Universidade Federal de Itajubá (UNIFEI).

The aviation sector accounts for approximately 3% of global energy demand and 10% of the energy consumed in the transport sector, contributing around 2.5% of anthropogenic carbon dioxide emissions (IEA, 2024b). Despite its modest share, the sector has not been excluded from the growing focus on decarbonising economic activities.

In 2010, the International Civil Aviation Organization (ICAO) set ambitious targets for reducing greenhouse gas emissions from international flights: (a) a 1.5% average annual improvement in CO_2 emissions efficiency from 2009 to 2020; (b) carbon-neutral growth from 2020 onwards; and (c) a 50%

reduction in sectoral emissions by 2050 (ICAO, 2010). In 2022, ICAO member states committed to a long-term goal of achieving net-zero carbon emissions in aviation by 2050 (ICAO, 2022b). These ICAO initiatives operate under the regulatory framework of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

As such, the aviation sector—heavily reliant on fossil fuels, with a higher per capita energy intensity than other modes of passenger transport and requiring stringent quality controls and costly designs—faces significant challenges in making a sustainable energy transition.

Among the strategies proposed to achieve these decarbonisation goals, replacing fossil kerosene with biofuels is highlighted as the primary strategic measure. This approach not only enables effective emission reductions but also decreases the sector's dependency on fossil fuels. Especially in regions with favourable conditions for biofuel production, this route deserves attention, as indicated by a technical economic assessment of SAF potential production in Southeast Asia, exploring crops and residues as feedstock (IRENA, 2024a).

Given the stringent quality controls in the aviation industry, ICAO has mandated that alternative fuels must be drop-in fuels—functionally equivalent to fossil fuels and compatible with existing distribution chains and aircraft without modifications (CAAFI, 2019). As of mid-2024, eleven production pathways have been approved as suitable for producing drop-in aviation biofuels under the ASTM D7566 Standard Specification for Aviation Turbine Fuel Containing Synthesised Hydrocarbons (ASTM, 2020). These fuels can be blended with fossil jet fuel at maximum limits ranging from 5% to 50% by volume, depending on the pathway.

Approved pathways with a 50% blending limit include: (i) hydrotreatment of vegetable or residual oils (HEFA technology) (Pearlson, 2011); (ii) oligomerisation and hydrogenation of anhydrous ethanol or isobutanol (ATJ technology) (Staples *et al.*, 2014); and (iii) the Fischer-Tropsch (FT) process using syngas obtained from biomass gasification (Klerk, 2011).

In addition to being drop-in fuels, under ICAO goals, alternative fuels must also be certified as sustainable aviation fuels (SAF). By early 2024, sustainability criteria required that alternative fuels: (i) achieve at least a 10% reduction in greenhouse gas (GHG) emissions compared to fossil kerosene over their lifecycle; and (ii) originate from land not deforested after 2008, with due accounting for emissions from land-use change (ICAO, 2022a). From 2024 onwards, an additional twelve criteria were introduced, including water use, air pollution, waste generation, human rights, and food security.

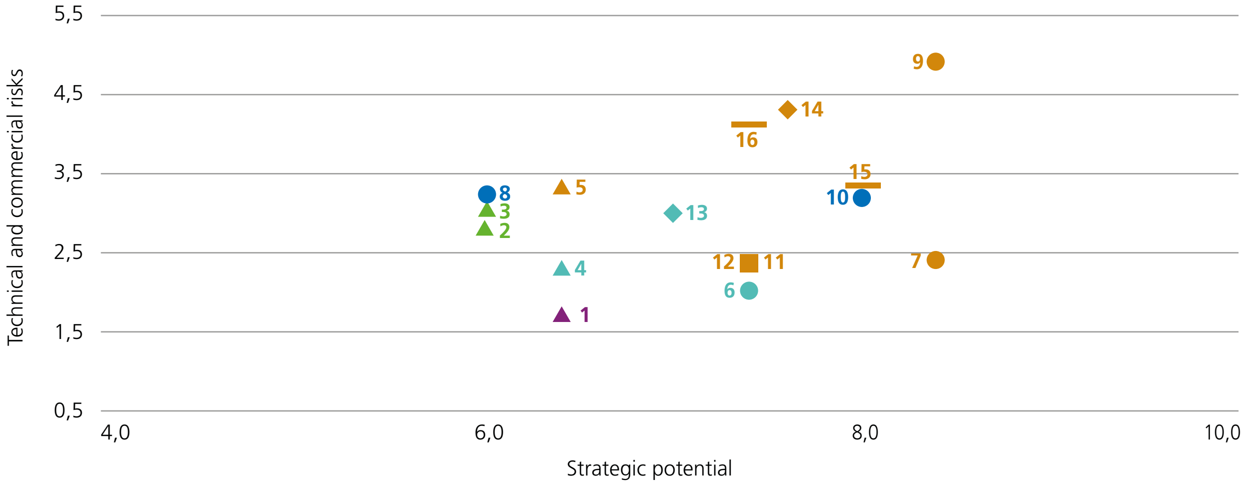
Initiatives to expand SAF usage in aviation have grown in recent years. From 2011 to mid-2024, over 750,000 commercial flights operated using SAF, 69 airports worldwide began regularly supplying SAF, and approximately 25 million cubic metres of SAF are projected to be produced by 2030, based on commitments in policies and commercial agreements (Aviation Benefits, 2024).

4.5.1. Prospects for SAF technologies and feedstocks in Brazil

Global SAF initiatives create a new market for biofuel production and use, which is of strategic interest to Brazil given its recognised expertise and favorable conditions in this sector. The Brazilian aviation sector accounts for approximately 2% of global aviation operations, including domestic flights (ANAC, 2020), and aircraft manufacturers based in the country. In this context, in 2024, the Brazilian government established the National Programme for Sustainable Aviation Fuel (PROBIOQAV) under Law 14,993/2024, setting targets for reducing GHG emissions in domestic operations: a 1% reduction by 2027, increasing to 10% by 2037.

As a new technological frontier, still in its phase of maturation and process learning, a wide range of production processes is under discussion, which expands further when considering the various classes of feedstocks that can be utilised. In 2014, to define the most promising alternatives, Brazil's SAF production potential was evaluated via a detailed roadmap involving numerous collaborators from the public and private sectors, academia, and non-governmental organisations (Cortez *et al.*, 2014).

GRAPH 15. Multicriteria analysis of SAF technologies and feedstocks in Brazil



1	HEFA – Hydrotreatment of oleaginous biomass (average values)
2	HEFA – Hydrotreatment of animal fat
3	HEFA – Hydrotreatment of used cooking oil
4	HEFA – Hydrotreatment of lipids from sugar-based biomass
5	HEFA – Hydrotreatment of lipids from lignocellulosic biomass
6	ATJ – Alcohol-to-Jet from alcohols derived from sugar-based biomass
7	ATJ – Alcohol-to-Jet from 2G alcohols derived from lignocellulosic biomass
8	ATJ – Alcohol-to-Jet from 2G alcohols derived from residual gases
9	ATJ – Alcohol-to-Jet from 2G alcohols derived from synthesis gas
10	ATJ – Alcohol-to-Jet from 2G alcohols derived from municipal solid waste
11	FT – Fischer-Tropsch from lignocellulosic biomass
12	FT – Fischer-Tropsch from bio-oil/bio-char derived from lignocellulosic biomass
13	DSCH – Direct hydrocarbons from sugar-based biomass
14	DSCH – Direct hydrocarbons from lignocellulosic biomass
15	FP – Fast pyrolysis of lignocellulosic biomass
16	HTL – Hydrothermal liquefaction of lignocellulosic biomass

Source: Prepared by the authors based on Cortez *et al*. (2014).

4.5.2. Performance of the ATJ pathway for SAF production from ethanol

Several studies have reported on the performance of alcohol-to-jet (ATJ) pathways approved for producing aviation biofuels from ethanol. As mentioned earlier, ethanol molecules are dehydrated into ethylene, followed by oligomerisation and hydrogenation, which can produce aviation biofuel, naphtha, and diesel. Naturally, process design can influence yields, as shown in Table 10.

TABLE 10. Reported yields for SAF production via the ATJ pathway

PARAMETER/REFERENCE	DE JONG *ET AL.* (2017)	KLEIN *ET AL.* (2018)	MIT MODEL (ICAO, 2024)	JRC MODEL (ICAO, 2024)
Input				
Ethanol (t)	1.00	1.00	1.00	1.0
Hydrogen (kg)	8.0	11.0	9.1	6.1
Electricity (kWh)	220.0	200.0		154.0
Natural gas (GJ)	0.6	-		6.6
Output				
SAF (t)	0.13	0.27	0.34	0.60
Diesel (t)		0.02	0.09	
Naphtha (t)	0.43	0.13	0.12	
Fuel oil (t)			0.03	

Source: Prepared by the authors.

For the results reported by the MIT and JRC models—both used in calculating the default emission values for the ATJ pathway under CORSIA (ICAO, 2024)—the calorific values of the products were assumed as per the GREET Programme (ANL, 2020).

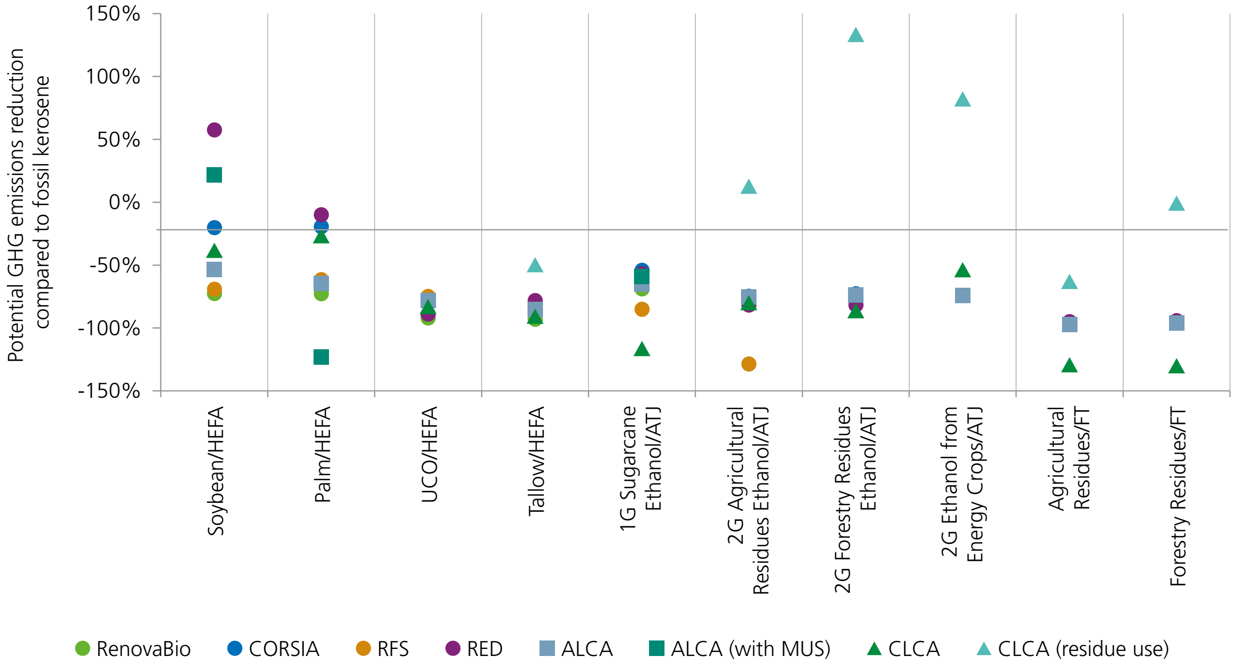
4.5.3. Environmental and economic assessment of SAF technologies

The environmental performance of biofuels, particularly concerning greenhouse gas (GHG) emissions, depends on the product's lifecycle and the methodological assumptions adopted in the analysis. Nonetheless, as reported by Capaz *et al.* (2020a), aviation biofuel derived from sugarcane ethanol under Brazilian conditions via the ATJ pathway could achieve GHG reductions of at least 50% compared to fossil kerosene across various regulatory frameworks and methodological approaches.

In their study, the authors assessed lifecycle GHG emissions for several aviation biofuel pathways in the Brazilian context, evaluating feedstocks ranging from residual biomass, such as fats and lignocellulosic waste, to well-established raw materials like soybean oil and sugarcane. Graph 16 presents the results for the evaluated cases.

Using an attributional approach (not accounting for potential emissions reductions from co-product substitution, such as surplus electricity), the carbon footprint ranged from 27.3 to 40.9 gCO_2e/MJ including land-use change emissions. The default value suggested for SAF from Brazilian sugarcane ethanol is 32.8 gCO_2e/MJ, which includes land-use change emissions (8.7 gCO_2e/MJ). When accounting for consequential emissions, the carbon footprint of SAF from Brazilian sugarcane ethanol could range from -14 to 13 gCO_2e/MJ, depending on US regulatory frameworks. This convergence of results was not observed for other pathways, even those based on waste.

GRAPH 16. GHG reduction/mitigation from using aviation biofuels compared to fossil kerosene



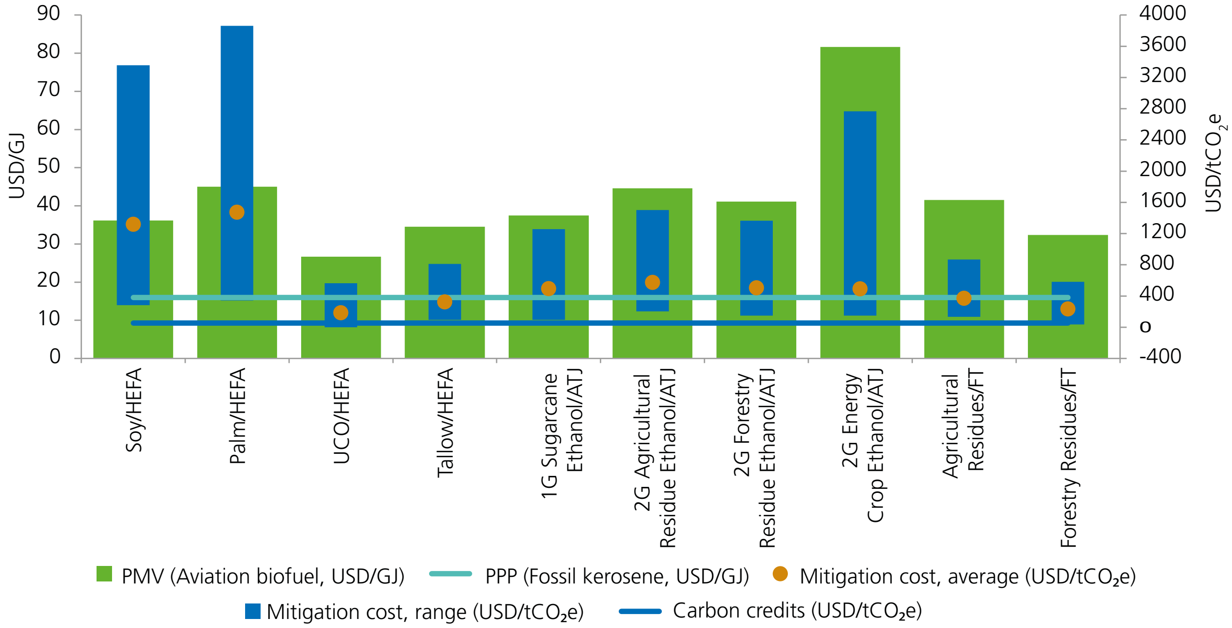
Regulatory Schemes: RenovaBio (Brazil), CORSIA (International), RED (Europe), RFS (United States).
Methodological Approaches: ALCA (Attributional) and CLCA (Consequential).
Acronyms: LUC: Land-use change; UCO: Used cooking oil; GRS: Gases from steelmaking.

Source: Capaz *et al*. (2020a).

When considering other environmental impact categories, such as those recently incorporated into the sustainability criteria of CORSIA (ICAO, 2022a), it is essential to rigorously account for local impacts from agrochemical and fertiliser use during the agricultural stage of sugarcane ethanol-based SAF production, as well as atmospheric emissions from ethanol processing (Capaz *et al.*, 2020b). In this regard, ethanol has been extensively and thoroughly studied due to its widespread production and use as a vehicle fuel.

While lower emissions represent a clear advantage for aviation biofuels, the economic viability of production pathways remains the main barrier to widespread implementation. This is also the case for SAF derived from sugarcane ethanol, which can cost up to twice as much (USD 37/GJ) as the average price of fossil kerosene sold in Brazil (USD 16/GJ), as shown in Graph 17.

GRAPH 17. Costs associated with aviation biofuel production in Brazil*



PPP: Price paid to the producer; PMV: Minimum selling price, excluding taxes; ORF: Used cooking oil; GRS: Residual gases from steelmaking.

*USD values for 2019.

Source: Adapted from Capaz *et al*. (2021).

For SAF produced via the ATJ pathway, ethanol accounts for approximately 80% of total costs, highlighting its significant influence on the pathway's viability (Capaz *et al.*, 2021). The minimum selling price of SAF derived from sugarcane ethanol is comparable to the estimated price for the soybean oil-based pathway, with both identified as short-term strategic alternatives for SAF production in Brazil. Pathways based on fatty waste residues or thermochemical routes using forest waste may appear slightly more attractive; however, feedstock availability or technological maturity remain challenges, as previously noted in Graph 15.

The mitigation costs of aviation biofuels indicate the level of remuneration required for the carbon avoided through their use to make them competitive with fossil kerosene. In this context, as reported by Capaz *et al.* (2021) and illustrated in Graph 17, the average mitigation cost of biofuels in all analysed scenarios remains significantly higher than the value of carbon credits currently available on the market, even considering future projections (up to USD 55.2/tCO_2e). In other words, when regulations allow, investing in carbon credit projects to meet reduction targets becomes more attractive than directly investing in SAF production and use.

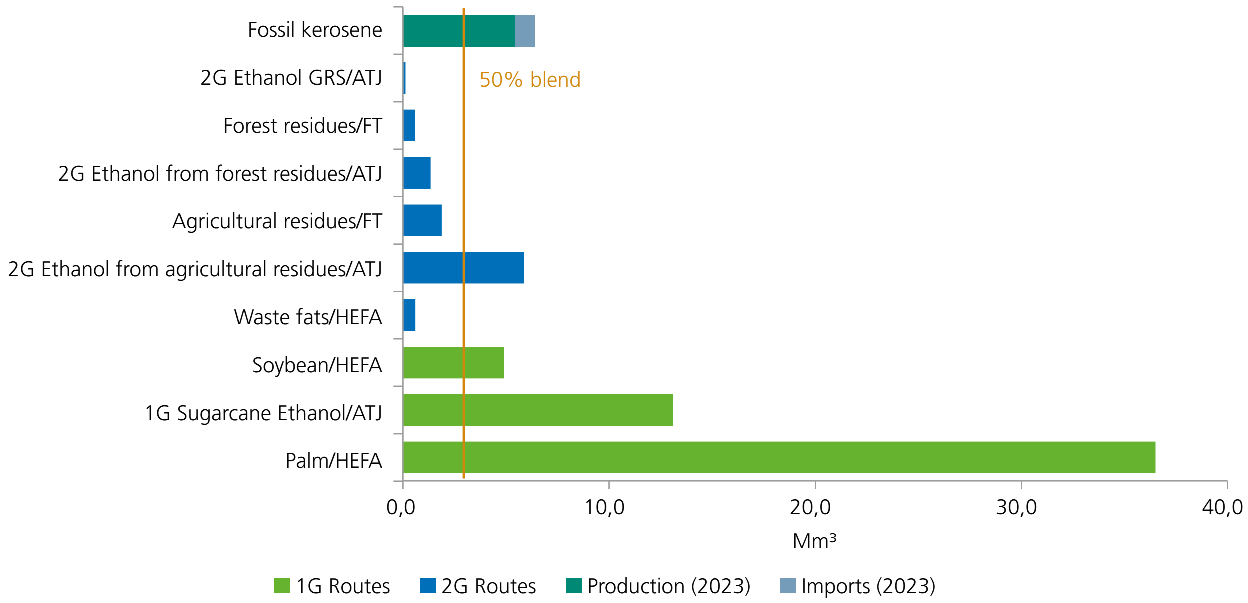
However, given its high GHG reduction potential and relatively competitive production costs, the sugarcane ethanol-based pathway presents mitigation costs (USD 495/tCO_2e) lower than those of vegetable oil-based pathways (USD 1,300–2,300/tCO_2e) and approaches those of waste-based pathways (USD 185–575/tCO_2e). Under optimal conditions, such as economies of scale, reduced feedstock costs, and high jet fuel prices, the sugarcane ethanol pathway could even approach the estimated value of carbon credits.

4.5.4. Potential for SAF production under Brazilian conditions

Based on the assumptions outlined by Capaz *et al.* (2021), the total SAF production from the pathways discussed in this chapter could exceed the demand for fossil kerosene in Brazil, which amounted to approximately 6.4 million m^3 in 2023 (EPE, 2024c). Notably, in recent years, 15–20% of this kerosene has been imported, as shown in Graph 16. If the maximum blending limit currently allowed for SAF in fossil jet fuel (50% for the mentioned pathways) is considered, the potential becomes even more significant.

Regarding production pathways, biofuel production from waste-based routes (2G) could match the total volume of kerosene consumed in Brazil. Among agricultural feedstock-based routes, although soybean oil is seen as the most viable short-term option (Cantarella *et al.*, 2015), the ATJ pathway using sugarcane ethanol, with its strong environmental and economic performance, offers numerous advantages.

GRAPH 18. Potential for aviation biofuel production under Brazilian conditions



1G: First generation; 2G: Second generation; GRS: Residual gases from steelmaking.

Source: Adapted from Capaz *et al.* (2021).

According to Cervi *et al.* (2020), approximately 13 Mm^3 of SAF from sugarcane ethanol could be produced using 3.9 Mha of degraded land or pasture areas in Brazil. Even under more conservative yield assumptions, SAF derived from sugarcane would suffice to meet domestic jet fuel demand, assuming the maximum blending limit is applied. Furthermore, the Sugarcane Agroecological Zoning (Manzanatto *et al.*, 2009) and recent expansion trends (Novaes *et al.*, 2017) indicate that around 8.9 Mha, predominantly used for livestock, could be suitable for sugarcane expansion, potentially yielding 30 Mm^3 of SAF via the ATJ pathway.

To meet the projected ethanol demand in 2034, an additional 0.4 Mha may be required (EPE, 2024d), underscoring the considerable potential for expanding sugarcane cultivation dedicated to aviation biofuel production. Additionally, integrating sugarcane with other crops or livestock systems could further enhance sustainability during expansion (Souza, S.P. *et al.*, 2012; Souza, N.R.D. *et al.*, 2019).

The palm-based pathway also presents opportunities for SAF production. However, expansion of this crop into degraded areas (EMBRAPA, 2010) must consider risks such as deforestation due to proximity to native forests and the lack of infrastructure for product transportation (Branford & Torres, 2018).

Brazil's expanding multi-cropping maize ethanol production, discussed in the previous chapter, significantly bolsters the country's biofuel supply. Consolidating the ATJ pathway using maize ethanol under Brazilian conditions is already recognised as a strategic potential (EPE, 2024c).

Recognising the strategic potential of SAF production in Brazil, particularly from environmental and economic perspectives, several initiatives are advancing, though not yet utilising ethanol. Recently, Brazil announced the construction of three aviation biofuel plants, two of which will be co-located with existing oil refineries. These plants, with a combined annual production capacity of 1.0 million m^3, are expected to start operations within five years. Feedstocks will include soybean oil, palm oil, tallow, and maize ethanol.

Other projects are under negotiation (EPE, 2024c). The three announced projects alone could meet up to 12% of Brazil's estimated aviation fuel demand from 2030 to 2033 and ensure compliance with 38% of CORSIA's reduction targets.

4.6. Carbon capture and use in bioethanol production

This section is based on a technical note prepared for this book by Arnaldo Cesar Silva Walter and Sara Valencia, from Universidade Estadual de Campinas (UNICAMP).

Carbon capture and storage (CCS) is a key strategy for reducing greenhouse gas (GHG) emissions. CCS involves processing carbon dioxide (CO_2), for instance from industrial processes or energy systems, by separating it from other gases, capturing it, compressing (or liquefying), and transporting it to a geological storage site for long-term containment. Variations of CCS technology include direct air carbon capture and storage (DACCS), which involves capturing CO_2 directly from the atmosphere, and bioenergy with carbon capture and storage (BECCS), which integrates CCS with bioenergy systems.

These technologies are classified as carbon dioxide removal (CDR) methods, removing CO_2 from the atmosphere either directly or indirectly via photosynthesis. CCS stages, such as CO_2 capture and geological injection, are mature technologies widely used in natural gas processing and enhanced oil recovery (EOR). However, CCS adoption remains less advanced in other energy sectors, such as cement and chemical production, in which it also offers mitigation potential (IPCC, 2023).

A related technological approach, carbon capture, utilisation, and storage (CCUS), refers to converting captured CO_2 into products. CCUS encompasses a suite of technologies that can play a critical role in meeting global energy and climate goals (IEA, 2022a). Captured CO_2 can be utilised to produce fuels such as methanol, synthetic hydrocarbons and chemicals (IEA, 2020). For instance, CO_2 can be converted into synthetic methane (SNG) or liquid hydrocarbons such as synthetic gasoline and diesel, using the Fischer-Tropsch process, which requires combining CO_2 with green hydrogen (produced with zero CO_2 emissions). CO_2 can also be used in manufacturing urea, an essential fertiliser component, and in producing high-performance plastics like polycarbonates.

However, CCS implementation faces several barriers, including technological, economic, institutional, ecological, environmental, and sociocultural challenges. Global CCS deployment indicators currently fall far short of the intermediate targets required to limit global warming to 1.5-2°C this century. Overcoming these barriers requires specific policies, economic instruments, increased public support, and technological innovation (IPCC, 2023).

4.6.1. BECCS projects: current status and prospects

As discussed, BECCS systems combine sustainable bioenergy use with CCS and are crucial for achieving negative emissions in the energy sector. Negative emissions occur when biogenic carbon removed from the atmosphere during biomass growth is captured and permanently stored (Santos *et al.*, 2019). This is achieved only when the amount of CO_2 captured exceeds the emissions generated across the entire BECCS value chain, including biomass cultivation (Tanzer & Ramirez, 2019).

In its 2°C scenario (2DS), the IEA set intermediate targets of capturing 60 $MtCO_2$ through BECCS by 2025 and 187 $MtCO_2$ by 2030 to achieve net-zero emissions by 2050 (IEA, 2017). However, as of 2024, all operational BECCS projects combined capture less than 2 $MtCO_2$ annually.

Table 11, based on IEA and Global CCS Institute data, summarises the seven operational BECCS projects. In total, five projects capture CO_2 during ethanol fermentation, while two demonstration projects focus on CO_2 capture from biomass combustion. Among these, the Drax Project in the UK stands out for its planned CO_2 capture from wood pellet combustion in a 660 MW power plant. In its first commercial phase (2027), Drax is expected to capture 4.3 $MtCO_2$ annually, increasing to 8.0 $MtCO_2$ by 2030.

TABLE 11. BECCS projects in operation, commercial phase or demonstration

PROJECT	LOCATION	CATEGORY	CAPACITY ($MTCO_2$/YEAR)	CO_2 SOURCE
Arkalon CO_2 Compression Facility	Kansas, United States	Commercial facility	0.31	Ethanol
Bonanza BioEnergy CCUS	Kansas, United States	Commercial facility	0.16	Ethanol
ADM Illinois Industrial Carbon Capture and Storage	Illinois, United States	Commercial facility	0.5	Ethanol
Midwest AgEnergy Blue Flint ethanol	North Dakota, United States	Commercial facility	0.2	Ethanol
Red Trail Energy BECCS Project	North Dakota, United States	Commercial facility	0.18	Ethanol
Mikawa Power Plant BECCS Fukuoka Prefecture	Japan	Pilot and demonstration	0.18	Biomass combustion
Drax BECCS Project	United Kingdom	Pilot and demonstration	1 tonne/day	Biomass combustion

Source: Prepared by the authors based on Global CCS Institute (2024) and IEA (2024d).

According to the IEA (2024), in the coming years, 63 new projects are expected to be implemented for capturing CO_2 from fermentation during ethanol production. The majority (51) are planned in the United States, followed by five in the United Kingdom, three in Canada, and one each in Hungary, Brazil, Uruguay, and Chile.

The Brazilian project, FS Lucas do Rio Verde Biorefinery, is scheduled to begin operations in 2030, with an estimated capture capacity of 0.423 $MtCO_2$ per year. In the areas of electricity and heat generation, the Global CCS Institute (2024) highlights five significant projects, three of which are under construction: Shell Energy and Chemicals Park Rotterdam, in the Netherlands, and Hafslund Oslo Celsio Waste-to-Energy Plant, in Norway, both slated to begin operations in 2024, as well as Ørsted Avedøre Power Station, in Denmark, expected to be operational by 2027. Moreover, two additional projects are in advanced development stages: Stockholm Exergi BECCS, in Sweden, and Amager Bakke Waste to Energy, in Denmark.

While these initiatives demonstrate progress, larger demonstration projects with greater capacity are essential for the effective advancement of BECCS technology. In addition to overcoming inherent challenges in CCS implementation, establishing large-scale bioenergy systems is also critical (IEA, 2017).

4.6.2. Potential and costs of BECCS projects

The potential of BECCS systems is particularly noteworthy in Brazil, especially in the bioethanol production sector and the broader sugar-energy industry. Implementing CCS in this context could significantly reduce greenhouse gas (GHG) emissions. During ethanol production via sugar fermentation, a pure CO_2 stream is released, eliminating energy penalties for separation. According to Moreira *et al.* (2016), producing 28.5 million m^3 of ethanol in Brazil could cut CO_2 emissions by 27.7 million tonnes annually. For the recent 2023/2024 harvest, producing 35.6 million m^3 of ethanol (29.7 million m^3 from sugarcane and 5.9 million m^3 from maize) could capture slightly over 34 $MtCO_2$.

Table 12 summarises the estimated abatement costs in Brazilian sugarcane mills, considering only CO_2 released during fermentation. In its Sixth Assessment Report, the IPCC (2023) indicated BECCS system costs range from 13 to 355 USD/tCO_2, with the lowest values associated with fermentation-based CO_2 capture in ethanol production.

TABLE 12. Estimated costs of CO_2 mitigation for fermentation-based capture in bioethanol production

COST (USD/TCO_2)	OBSERVATIONS	REFERENCE
USD 27.2/tCO_2*	Capture cost in autonomous distilleries in São Paulo, considering a 100 km transport and storage distance	Moreira *et al.*, 2016
USD 25.5/tCO_2*	Enésima plant cost for CO_2 compression, transport, and storage in typical Brazilian mills, assuming a 100 km injection distance	Restrepo-Valencia & Walter, 2019
USD 50/tCO_2**	Abatement cost estimate in ethanol distilleries	Da Silva *et al.*, 2018
USD 45–95/tCO_2**	Initial value and learning effect reduction	Kemper, 2015
USD 42/tCO_2**		IEAGHG, 2018

*USD values for 2014.
**USD values for 2015.

Source: Prepared by the authors.

In typical industrial settings, CCS for fermentation-derived CO_2 may be implemented on a smaller scale, increasing costs due to lower capacity and significant transport expenses. Therefore, CO_2 capture in ethanol production must be optimised, potentially by creating hubs and integrating different transport modalities (Silva *et al.*, 2018). Alternatively, integrating CCS with cogeneration plants may improve the infrastructure viability of CO_2 transport (Tagomori *et al.*, 2018). However, achieving economies of scale could require additional CO_2 flows from fossil sources to increase capacity factors (Formann *et al.*, 2020).

Capturing CO_2 from biomass combustion in cogeneration systems involves significant energy penalties, primarily related to CO_2 compression power requirements and steam demand for regenerating absorbents (commonly amine-based). Combined with the high process steam demand in sugar and ethanol mills, these penalties can hinder CCS integration and impact project performance.

A study conducted on a typical Brazilian mill concluded that capturing CO_2 emissions from cogeneration systems, which traditionally burn sugarcane bagasse and, more recently, bagasse combined with sugarcane straw, could achieve at least three times the CO_2 captured during fermentation. For a BECCS system with a capture capacity of 1.09 $MtCO_2$/year (representing only 12% of the CO_2 from fermentation), the estimated cost ranges from 82 to 96 USD/tCO_2 (Restrepo-Valencia & Walter, 2019).

The studies also explored the integration of CCS into biomass integrated gasification combined cycle cogeneration systems (BIG-CC), which are not yet commercially available (Restrepo-Valencia & Walter, 2023a), and into thermoelectric plants using residual sugarcane biomass as fuel (Restrepo-Valencia & Walter, 2023b). For thermoelectric plants, the findings can be extended to facilities using other biomass types as fuel. For instance, with biomass costing USD 2.4/GJ, the estimated cost would range from 93 to 105 USD/tCO_2, enabling the capture of 2.6 $MtCO_2$/year and the annual generation of 1.55 TWh.

An alternative still under exploration is the production of synthetic hydrocarbons from CO_2 generated during fermentation and/or biomass combustion in cogeneration systems, using hydrogen produced via water electrolysis powered by electricity from residual sugarcane biomass. It is estimated that the carbon footprint of such fuels would be quite low.

Geological CO_2 storage can be considered the most critical phase of CCS due to the specific conditions required: large geological formations with depths greater than 800 metres, structures capable of trapping CO_2, and adequate porosity and permeability of the rock (Page *et al.*, 2020). Storage options can be categorised into three groups: saline formations (or saline aquifers), depleted oil and gas fields, and unconventional resources (igneous rocks, unmineable coal seams, and organic shales) (IEA, 2022b).

In Brazil, preliminary studies have estimated a CO_2 storage capacity of 2,000 gigatonnes (Global CCS Institute, 2017; Kearns *et al.*, 2017), albeit with a high degree of uncertainty. The publication *Atlas de Captura de Carbono Brasileiro* outlined the existing pipeline infrastructure at the time and classified potential storage areas (basins) based on their prospectivity (Ketzer *et al.*, 2016). To date, this remains the most comprehensive study available.

A macro-level assessment of CO_2 storage capacity is a starting point, but further evaluation is needed to determine feasibility. Large-scale CCS implementation requires detailed knowledge of storage potential and associated costs. The distance between these sites and the generation sources will significantly influence feasibility. Of the potential CO_2 storage locations identified, only a small number are expected to qualify as truly suitable. The International Energy Agency (IEA, 2022b) estimates that, following initial studies, it could take three to ten years to establish conditions for effective commercial storage.

4.7. Renewable hydrogen from bioethanol

Hydrogen is the simplest and most abundant chemical element, representing 75% of the universe's mass; however, it constitutes less than 1% of the mass of our planet, almost always combined with other elements, such as oxygen in water. Hydrogen's properties differ significantly from those of other gases, presenting advantages such as a high calorific value, and challenges such as very low density (less than 10% of the density of air), high flame speed, and, notably, it is one of the few gases that heat up when expanding, requiring cooling when safely filling tanks that must withstand very high pressures, up to 900 atm.

Currently, hydrogen is used mainly as an industrial input in petroleum refining and ammonia production, with a global demand of around 95 million tonnes per year, predominantly produced from natural gas and light hydrocarbons. This type of hydrogen results in significant fossil CO_2 emissions and is therefore not the desirable form of hydrogen.

Within the framework of the global energy transition, green hydrogen emerges as the preferred option. Produced with renewable energy, it has the potential to replace carbon-intensive hydrogen as an industrial feedstock across multiple sectors while also fostering the development of new markets in the energy sector.

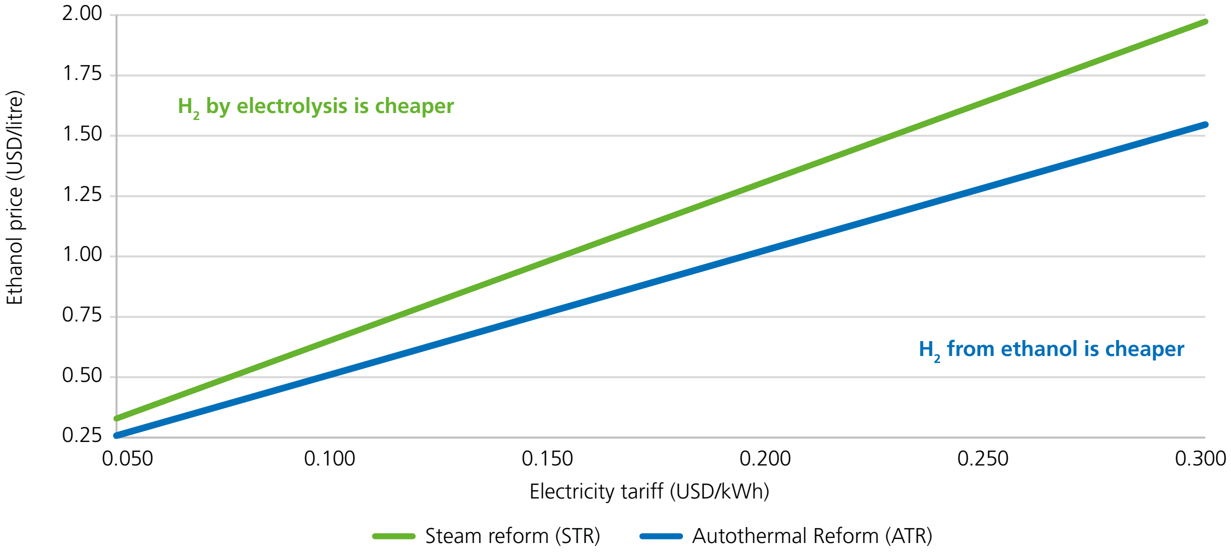
4.7.1. Processes for producing renewable hydrogen

Of the several available pathways for renewable hydrogen production, the most promising technological options include:

- **from electricity**, via electrolysis, in which water is separated into its components. This is the most mature and widely adopted process in projects currently being implemented, in which electricity must be produced from renewable sources,
- **from biomass**, via three alternatives: (1) reforming of biomethane, the main component of biogas; (2) bioethanol reforming processes, which are technologically mature; and (3) a low-cost solid biomass gasification process, producing gases with lower hydrogen content, which can also be purified. The last process is under development, and its economic feasibility has not yet been demonstrated.

Bioethanol reforming processes are endothermic and present essentially two alternatives: (a) steam reforming of ethanol (STR), which requires an external source of heat to operate at temperatures usually from 400°C to 650°C; and (b) autothermal reforming of ethanol (ATR), in which partial oxidation of ethanol supplies the heat required for the reaction. Although STR is currently more promising for practical applications, consuming about 7.6 litres of bioethanol per kg of hydrogen, ATR offers notable advantages such as reduced temperature, reduced coking, and longer operation, consuming around 9.7 litres of bioethanol per kg of hydrogen. Both routes have been the subject of intensive studies aimed at developing better catalysts (Feng *et al.*, 2023; Chen *et al.*, 2023).

GRAPH 19. Renewable hydrogen production parity curves for electrolysis and ethanol reform considering only costs of inputs (electricity and ethanol)



Source: Prepared by L. A. Horta Nogueira.

To compare the costs of hydrogen production via electrolysers and ethanol reforming, excluding equipment and installations investments (which are certainly higher for electrolysis) and considering only direct input costs (electricity and ethanol), it is possible to draw a parity or indifference curve, depicted in Graph 19. On these blue (ATR process) and green (STR) lines, hydrogen costs are equal; below these lines, hydrogen from ethanol is cheaper than hydrogen from electricity. Considering the typical range of prices in recent years, USD 0.40 to 0.60/litre of ethanol and USD 0.150 to 0.200/kWh for industrial electricity, ethanol is competitive with electricity, which will be the preferred option only at very low tariffs.

4.7.2. Initiatives for renewable hydrogen from biomass in Brazil

For countries such as Brazil, with a good endowment of natural resources (soil, climate, *etc.*) and experience in bioenergy technologies, biomass presents a viable alternative with effective potential in the hydrogen economy. In addition to Nissan’s prototype electric vehicle presented in Chapter 2, which uses electricity generated by a fuel cell powered by hydrogen produced on board via ethanol reforming, some other innovative initiatives have been implemented, as presented below.

Hydrogen from ethanol reformers

The company Hytron, based in Sumaré, São Paulo, was founded in 2003 by five young PhDs as a spin-off from the Hydrogen Laboratory of the State University of Campinas (UNICAMP) supported by the São Paulo Research Foundation (FAPESP), and focused on technologies for the production, purification, and use of hydrogen. In 2020, Hytron was incorporated into the NEUMAN & ESSER Group from Aachen, Germany, reinforcing its expertise in integrating systems while maintaining its focus on hydrogen.

Among its products, using proprietary technology, Hytron offers a line of hydrogen production reformers for ethanol and biomethane (from biogas), with a rated capacity of up to 750 kg H_2/day at 10 bars, and purity of up to 99.999%. This corresponds to a consumption of 7.65 litres of ethanol and 2.35 kWh of electricity or 4.85 Nm^3 of biomethane and 4.71 kWh of electricity per kilogram of hydrogen produced (NEA Hytron, 2022).

FIGURE 35. Unit for hydrogen production by ethanol reforming, installed at the University of São Paulo, developed by Hytron (NEUMAN & ESSER Group) for Shell Brasil, through the ANP R&D Program

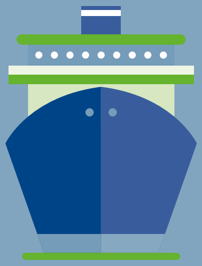
Photo: Antonio Marin/Courtesy of Hytron (NEUMAN & ESSER Group).

These reformers are offered as integrated and autonomous "turn-key" solutions, including feed treatment, reforming and shift conversion, pressure swing adsorption (PSA) gas purification, purity monitoring, thermal management and utilities, controls, and containers for outdoor installation. Recently, in a project joining Shell Brasil, Hytron, SENAI and Raízen, one unit was installed in the University of São Paulo (USP) campus to demonstrate this technology, fuelling hydrogen-powered buses.

Production of green ammonia using hydrogen produced by reforming biomethane generated via the biodigestion of ethanol vinasse

In 2021, the companies Raízen and Yara formed a consortium to produce green ammonia using hydrogen derived from biomethane from vinasse biogas. An interesting feature of this project is that biomethane will be produced in Piracicaba, injected into the Gasbol gas pipeline, and transported 236 km to the coast of São Paulo, where it will be used to produce hydrogen and then ammonia with a low carbon footprint.

As an illustrative exercise, considering that 4.85 m^3 of biomethane yields 1 kg of hydrogen, which when combined with nitrogen produces 5.67 kg of ammonia, a potential production of 6.0 million m^3/day of biomethane in Brazil by 2027—as estimated by the Brazilian Biogas Association (ABiogás, 2024)—could result in around 2.56 million tonnes of green ammonia per year, which accounts for 64% of the apparent Brazilian consumption of nitrogen fertiliser in 2020 (approximately 4 million tonnes). Capex and Opex costs for biomethane-based green ammonia are lower than for electricity-based green ammonia, as ammonia plants are already in place and the technology is well established.



Part 2

BRAZIL'S EXPERIENCE IN SUSTAINABLE BIOETHANOL

Bioethanol has been produced and used as a transport fuel in Brazil for nearly a century, consolidating in recent decades as a competitive and sustainable alternative. The following chapters provide a comprehensive review of this energy option in the Brazilian context, revisiting its history, the development of the legal framework and outlining the perspectives of government and economic stakeholders. The evolution of productivity and sustainability indicators is strongly supported by agronomic and industrial research, as well as technological improvements enabled by process integration and recycling, cogeneration and anaerobic digestion. Particular attention is given to the sustainability of bioethanol production, addressing aspects such as energy efficiency, land use and carbon emissions, and introducing the RenovaBio programme.

Main outcomes of this process include:

- In the Brazilian light vehicle fleet—37.3 million automobiles (2023)—85% can run on pure bioethanol.
- Bioethanol represented 43% of energy demand of this fleet in gasoline equivalent (2023).
- Between 1975 and 2023, 3.6 billion barrels of petrol were replaced with bioethanol, saving more than 725 billion US dollars (as of December 2023), considering the avoided external debt costs.
- Between 1975 and 2023, more than 700,000 direct jobs and over 2 million indirect jobs were created.
- Over the past 50 years, the use of bioethanol has prevented the emission of 1.37 billion tonnes of CO_2 in Brazil, without considering the effect of electricity production in mills using sugarcane by-products.

5.

Evolution of bioethanol production and use in Brazil

One of the most interesting aspects of the energy matrix in Brazil is the contribution of ethanol produced from sugarcane and used to replace gasoline.

J. Goldemberg,
Energy in Brazil: Past and Future, 2018.

The previous chapters focused on the general aspects of bioethanol production and use, considering its application in mobility, reviewing technological pathways involving sugarcane and maize and presenting innovative technologies that have been studied and progressively adopted. These advancements have led to product diversification, efficiency gains and reduced environmental impacts. Although focusing on Brazil, the processes and technologies discussed can also be applied in other countries where bioethanol production and use have been effectively implemented.

The following chapters delve deeper into the Brazilian experience, examining the evolution of bioethanol use and its implications from multiple perspectives. The country's nearly century-long history of biofuel production and consumption provides valuable insights, from the gradual development of an institutional framework to the evolution of agro-industrial technical parameters. This trajectory exemplifies productivity gains and the progressive expansion of environmental benefits, as reflected in sustainability indicators. Given Brazil's context, sugarcane takes centre stage, though maize ethanol—of growing importance—is also considered. Additionally, there are brief mentions of biodiesel, biomethane and other more recently introduced, yet equally relevant, biofuels in Brazil.

The following paragraphs review the historical development of bioethanol as a fuel in Brazil, shaped by the efforts of numerous visionary individuals and dedicated technical experts. Concurrently, a legal and institutional framework was gradually established, allowing this energy alternative to become a regular component of Brazil's energy matrix. Next, complementary perspectives are provided on the current and future landscape of bioethanol production in the country, outlining the main characteristics of the production sector based on insights from the Energy Research Office (EPE) and the Brazilian Sugarcane and Bioenergy Industry Association (UNICA). The subsequent section, drawing on a Pecege study, analyses productivity and economic margins in ethanol production in Brazil, highlighting a continuous process of technological innovation. This is followed by an examination of the significant role of research and technological development in refining methods, equipment and processes that have enabled the sugarcane agroindustry to establish itself as a sustainable energy source. Emphasising the importance of knowledge generation and application, this chapter concludes with a review of the contributions of modern genomics to productivity gains and the long-term viability of sugarcane cultivation in Brazil.

5.1. A Historical perspective on bioethanol in Brazil

Sugarcane, the primary raw material for Brazilian bioethanol, has been cultivated in Brazil since 1532. It was introduced by Martim Afonso, the first Portuguese coloniser, with the aim of establishing sugar mills similar to those that existed at the time in the Azores. The species adapted well to the Brazilian soil and was extensively cultivated throughout the colonial period, yielding positive results along the country's coastline. Dozens of sugar mills were built, particularly in the Recôncavo Baiano region and in Pernambuco, driving nearly two centuries of Brazil's most significant colonial economic cycle. At that time, sugar was the sole product derived from sugarcane, obtained via simple and inefficient processes, with only a limited production of aguardente (a sugarcane spirit) from molasses.

FIGURE 36. *Engenho de Itamaracá*, 1647, by Frans Post

Note: This image is a Joan Blaeu's inset of the map of Brazil *Engenho de Itamaracá*, by Frans Post, featured in Gaspar Barlaeus's *Rerum per octennium in Brasilia et alibi gestarum: sub praefectura illustrissimi comitis I*. Mauritii Nassaviae &c. comitis, published in 1647 and edited by Blaeu. The original map by Frans Post can also be found in *O Brasil Holandês sob o Conde Maurício de Nassau*, translated to Portuguese by Cláudio Brandão in 1940, available at http://www2.senado.leg.br/bdsf/handle/id/227290.

Source: Blaeu (1665).

With the expulsion of the Dutch from the Northeast and the expansion of the sugar industry in the Caribbean in the mid-17th century, Brazil's relative importance in sugar production declined. However, sugarcane cultivation remained a key economic activity in the country. It was revitalised in the last century with the establishment of the Institute of Sugar and Alcohol (IAA) in 1933 at a time when the use of automotive bioethanol was emerging. From that period onwards, the sugarcane agroindustry also began expanding into the Southeast Region, initially linked to the decline of coffee plantations and later to the growth of the domestic market (Szmrecsányi, 1979).

5.1.1. Early steps in the use of bioethanol as a fuel

In 1903, the findings of the First National Congress on Industrial Applications of Alcohol already recommended the implementation of automotive bioethanol production in Brazil (Goldemberg, 2018). With the establishment of the Fuel and Mineral Experimental Station (EECM) in 1920—later to become the National Institute of Technology (INT). Tests were conducted on vehicles powered by bioethanol, which at the time was known as *álcool-motor* (motor alcohol). These tests demonstrated that bioethanol could serve as a substitute for imported gasoline, a product that was both scarce and increasingly expensive (Castro & Schwartzman, 1981).

FIGURE 37. Ford Model A adapted for pure bioethanol use, used by EECM in demonstrations in 1925

Photo: Acervo INT (INT, 2002).

Amongst the pioneers in the use of bioethanol as a vehicle fuel were Heraldo de Souza Mattos, who in 1923 participated in motor races using pure hydrous bioethanol; Fernando Sabino de Oliveira, author of O *álcool-motor e os motores a explosão* (Motor alcohol and internal combustion engines), published in 1937; and Lauro de Barros Siciliano, who authored dozens of technical studies on the use of bioethanol in engines. These individuals carried out bench tests and road trials, seeking to persuade both the private and public sectors (Vargas, 1994).

During this period, some sugar mills even began to market bioethanol as a fuel. A pioneer in this regard was the Serra Grande Mill (USG) in Alagoas, where engineer Salvador Lyra developed tests from 1924 onwards that led to the launch of USGA fuel, a blend of bioethanol, ether, and castor oil. This fuel was successfully distributed across various cities in northeastern Brazil (Nastari, 2024).

FIGURE 38. Advertisement for bioethanol-based USGA fuel

O Pioneiro dos combustiveis nacionaes, a base de alcool, cuja efficiencia já está provada em um anno de ascendente consumo, em Pernambuco e Alagôas. Usar o combustivel nacional é dever dos bons patriotas

Usina Serra Grande -- Alagôas

O Jornal (RJ) - 17/9/1928 Usina Serra Grande, São José da Laje, Alagoas, Brasil.

Source: USG (2024).

Encouraged by the positive results of these early initiatives—and aiming to mitigate the impact of total dependence on imported petroleum-based fuels whilst also utilising the sugar industry's production surplus—the Brazilian government issued Decree 19,717 in 1931. Signed by President Getúlio Vargas, the decree mandated the compulsory blending of at least 5% anhydrous bioethanol into gasoline. Initially, this applied only to imported gasoline but was later extended to domestic gasoline as Brazilian refineries began processing imported crude oil (BRASIL, 1931).

Subsequently, the Institute of Sugar and Alcohol (IAA) was given the responsibility of setting prices, production quotas per mill and blend percentages. As a result, the use of bioethanol as a vehicle fuel—already known to the automotive industry for over a century—has been a regular practice in Brazil since 1931, virtually coinciding with the introduction of automobiles as a means of transport in the country.

5.1.2. The creation of the National Alcohol Programme (Proálcool)

The bioethanol content in Brazilian gasoline varied over the decades from 1931 onwards, averaging 7.5% until 1975, when the effects of the first oil shock made it necessary to expand the use of this biofuel in engines. Due to the rise in international oil prices, Brazil's oil import costs increased from USD 600 million in 1973 to USD 2.5 billion in 1974, causing a trade balance deficit of USD 4.7 billion, which had a growing impact on Brazil's external debt and inflation. A solution was urgently needed.

With this aim, in the first half of the 1970s, visionary entrepreneurs from the sugar industry, such as Lamartine Navarro Jr. and Cícero Junqueira Franco, began developing a proposal to reduce dependence on imported oil. Their plan combined the Sugar and Alcohol Institute's preference for the exclusive production of bioethanol in independent distilleries with the interest of Copersucar, the main sugar producers' cooperative, in utilising the idle capacity of distilleries attached to sugar mills. A document containing recommendations from discussions between the private sector and the government, based on this proposal, was submitted to the National Petroleum Council in March 1974 (Bertelli, 2007).

FIGURE 39. Prof. Urbano Ernest Stumpf (1916–1998), pioneer of modern pure bioethanol engines in Brazil

Photo: Personal collection (courtesy of Silvia Stumpf).

Another crucial factor in the government's decision to increase the use of bioethanol was President Ernesto Geisel's visit to the Aeronautics Technology Centre in São José dos Campos in June 1975. During this visit, he learned about the work carried out by Professor Urbano Ernesto Stumpf on bioethanol-fuelled engines. These studies involved gasoline with higher proportions of anhydrous bioethanol and experiments with engines running exclusively on hydrous bioethanol. On this occasion, it became evident that Brazil had a viable solution: on the supply side, the country could increase bioethanol production using the idle capacity of sugar mills, and on the consumption side, it could raise the bioethanol content in gasoline and even consider using pure bioethanol.

With these premises in mind, following further studies and discussions, the federal government established the National Alcohol Programme (Proálcool) through Decree 76,593, dated 14 November 1975, signed by President Ernesto Geisel (BRASIL, 1975). This decree introduced specific lines of financing, formally created the National Alcohol Commission (CNA) to oversee the programme and set a price parity between bioethanol and standard crystal sugar, encouraging the production of this biofuel, which had previously been a less valued by-product.

The programme initially set production targets of tree billion litres of bioethanol by 1980 and 10.7 billion litres by 1985. Incentives were also introduced to expand the production and use of bioethanol as a fuel, beginning with an increase in the proportion of anhydrous bioethanol added to gasoline. In the early years of Proálcool's implementation, the efforts of the Minister of Industry and Commerce, Severo Gomes, and his Secretary of Industrial Technology, José Walter Bautista Vidal, were decisive in shaping the initial phase of the programme. Later, from 1979 onwards, under Minister João Camilo Pena, Proálcool underwent its most significant expansion, laying the foundation for the consolidation of bioethanol as a fuel. Reflecting the vision of this pioneering generation, the book *Energia da biomassa – Alavanca de uma nova política industrial* (*Biomass energy—Lever for a new industrial policy*) highlighted the need to transcend conventional energy systems in favour of the "civilisation of photosynthesis" (Guimarães *et al.*, 1986).

With a legal framework highly favourable to bioethanol, its production grew significantly. Between 1975 and 1979, the production of anhydrous and hydrous bioethanol increased from 580,000 m³ to 3.676 million m³, surpassing the 1979 target by 15%. As the oil crisis worsened in 1979, with a further increase in oil prices, Proálcool was intensified, encouraging the use of hydrous bioethanol in adapted or purpose-built engines. In July 1979, Fiat launched the Fiat 147, the world's first mass-produced ethanol-fuelled car, an initiative soon followed by other car manufacturers in Brazil.

FIGURE 40. Fiat 147, the first factory-produced model designed to run exclusively on hydrous bioethanol

Photo: Fiat/Stellantis Media.

At that time, Brazil's dependence on imported oil was around 85%, accounting for 32% of total imports and causing even more severe economic impacts, which justified the ambitious goal of producing 10.7 billion litres of bioethanol by 1985. To achieve this, the federal government reinforced support for ethanol production through Decree 83,700 in 1979 (BRASIL, 1979), which created the National Alcohol Council (CNAL) to oversee Proálcool and the National Executive Commission on Alcohol (CENAL) to implement the programme (CGEE, 2007). Under these conditions, bioethanol production reached 11.7 billion litres in 1985, exceeding the initial target by 8%.

In summary, the set of incentives adopted under Proálcool at that time proved effective in motivating economic agents and promoting the necessary changes. These included: (a) setting progressively higher minimum levels of anhydrous bioethanol in gasoline, in collaboration with the automotive industry; (b) ensuring that the retail price of hydrous bioethanol remained lower than that of gasoline (at that time, fuel prices were controlled by the federal government across the entire production chain); (c) guaranteeing competitive remuneration for bioethanol producers, even when international sugar prices were more attractive than those for bioethanol (through a competitiveness subsidy); (d) offering favourable credit lines to expand production capacity; (e) reducing taxes (on new car sales and annual vehicle registration) for hydrous bioethanol-fuelled vehicles; (f) maintaining strategic stockpiles to guarantee supply during off-seasons; and (g) making it mandatory for gasoline stations to sell hydrous bioethanol, facilitated by raising the octane level of regular gasoline to values close to that of premium gasoline, allowing for the sale of only one gasoline type and freeing up at least one tank and pump at each station for hydrous ethanol sales.

During 1985, however, a shift occurred: a sharp drop in international oil prices, combined with rising sugar prices, discouraged bioethanol production and created difficulties, marking the end of Proálcool's initial expansion phase. In 1986, the federal government revised its incentive policies, reducing the profitability of the sugarcane agroindustry and further encouraging the diversion of sugarcane to sugar production for export. As a result of this governmental neglect and the absence of specific policies for bioethanol, by 1989, ethanol consumers faced supply shortages. The mechanisms for maintaining security stocks failed, prompting emergency measures such as reducing the bioethanol content in gasoline, importing bioethanol and blending gasoline with methanol as a substitute for bioethanol.

One major consequence of this supply crisis—particularly for a domestically produced fuel that had been heavily promoted with the slogan "*pode usar que não vai faltar*!" ("use it, it won't run out!")—was the loss of consumer confidence, which inevitably led to a decline in sales of ethanol-fuelled cars. After reaching 85% of all new vehicle sales in 1985, ethanol-only vehicles accounted for just 11.4% of sales by 1990 (Scandiffio, 2005). Only from mid-2003, with the introduction of flexible-fuel vehicles, did hydrous bioethanol consumption begin to rise significantly again.

In an attempt to counter this situation, the Brazilian government introduced Decree 94,541 in 1987, establishing regulations for the distribution, commercialisation and storage of ethanol fuel (BRASIL, 1987). Amongst other measures, this decree required Petrobras to purchase ethanol to maintain a two-month security stock and instructed the Sugar and Alcohol Institute to determine annual ethanol demand, setting production and commercialisation limits for ethanol producers.

Even during this uncertain period for bioethanol, independent studies highlighted the need to maintain the programme, proposing a slower growth rate while ensuring its continuity not only because of its environmental and social benefits but also because productivity improvements had made bioethanol competitive with oil priced at USD 30 per barrel (Serôa da Motta & Ferreira, 1988).

5.1.3. The opening of the fuel market in Brazil

Until the early 1990s, the fundamental structural characteristics of Brazil's sugarcane-based agroindustry, shaped by decades of strict State control, included government-supervised agricultural and industrial production, productive heterogeneity (particularly in sugarcane cultivation), limited utilisation of by-products and competitiveness largely based on low wages and extensive production. There were significant technological disparities between production units in the North-Northeast and Centre-South regions, and even within these regions, productivity and production scale varied considerably (CGEE, 2007).

As part of the administrative reforms introduced in the early 1990s, which redefined the State's role in the national economy, the Brazilian government initiated the process of liberalisation and institutional restructuring of the sugar-ethanol sector. With the dissolution of the Sugar and Alcohol Institute, responsibility for bioethanol-related matters was transferred in 1997 to the Inter-ministerial Council for Sugar and Alcohol (CIMA). This body was initially overseen by the Ministry of Industry and Commerce until 1999, when it came under the jurisdiction of the Ministry of Agriculture.

With the gradual withdrawal of cross-subsidies and freight equalisation mechanisms, along with the lifting of bioethanol price controls from 1991 onwards, the full liberalisation of prices in the sugar-ethanol sector began. In this context, a decree by the Ministry of Finance in 1996 led to the deregulation of anhydrous ethanol prices from May 1998 and hydrous ethanol prices from February 1999, thereby completing the market opening process. This marked the beginning of a new framework governing relationships between sugarcane producers, bioethanol producers, and fuel distribution companies, in which market-driven principles now prevail. Of the original legal and tax measures that helped consolidate bioethanol as a fuel in Brazil, only the differentiated taxation of hydrous ethanol remains, designed to maintain approximate price parity for consumers choosing between hydrous ethanol and gasoline.

Within this framework, the prices of both anhydrous and hydrous bioethanol are freely negotiated between producers and distributors. In the agro-industrial sector, sugarcane prices are also deregulated but are largely determined through a voluntary contractual model jointly coordinated by sugarcane growers and bioethanol and sugar producers. Under this model, the sugar content of the cane delivered for processing, as well as the sugar and bioethanol produced by mills, is converted into a common benchmark known as total recoverable sugars (TRS). According to this system, sugarcane growers are paid based on their actual contribution to production, measured by the TRS content of the raw material delivered to the agroindustry. The price of this TRS is determined by the economic performance of the final products—sugar and bioethanol—across both domestic and international markets. In São Paulo and neighbouring regions, this model is managed by the São Paulo State Council of Sugarcane, Sugar and Alcohol Producers (Consecana), established in 1997 and composed of representatives from all private sector stakeholders.

This restructuring of the roles and operations of economic players in the bioethanol industry did not occur overnight or without contention. Disputes arose between business owners who supported the existing legal framework, which guaranteed market stability and profits, and more progressive entrepreneurs who favoured a freer market with investment opportunities and productivity-based gains. Over time, and thanks to the advancements made, the new market-oriented model prevailed. A crucial factor in this transition was the establishment of a revised institutional framework that guided and reinforced the implemented transformations.

In the bioethanol agroindustry, this institutional restructuring was driven by Law 9,478 of 1997, which created two key institutions: the National Energy Policy Council (CNPE) and the National Petroleum Agency (ANP) (BRASIL, 1997). The CNPE is the highest federal government body responsible for coordinating and implementing energy policy guidelines, ensuring energy security, sustainability and resource efficiency. Amongst its responsibilities is setting directives for specific biofuel usage programmes and, since 2022, periodically defining and reviewing the required proportion of anhydrous bioethanol in gasoline. This proportion, which must fall between 17.5% and 18%, has mostly remained at 27% in recent years, though it has been adjusted at times based on market conditions and supply levels. Under the recently introduced Future Fuel Law, discussed later, this limit was increased.

In 2005, Law 11,097 officially renamed the ANP as the National Agency for Petroleum, Natural Gas and Biofuels, expanding its remit (BRASIL, 2005). The ANP is responsible for regulating, contracting and overseeing economic activities related to biofuels, implementing national biofuel policies, ensuring supply across Brazil and protecting consumer interests regarding price, quality and product availability.

More specifically, the ANP's responsibilities include authorising biofuel producers and distributors, enforcing legal and contractual regulations, promoting best practices for conservation and efficient biofuel use, maintaining records of industry-related information and setting biofuel quality standards. This last function is particularly important, requiring strong technical support and collaboration between bioethanol producers, engine manufacturers and environmental agencies. As discussed in Chapter 2, ANP resolutions define the specifications for anhydrous and hydrous bioethanol as fuel. Since its establishment, the ANP has expanded its role in the biofuels market, working in conjunction with other government bodies.

The institutional revision process for bioethanol was concluded in 2000 with the establishment of the Inter-ministerial Council for Sugar and Alcohol (CIMA) through Decree 3,546/2000 (BRASIL, 2000). This council is tasked with formulating policies related to the sugar-ethanol sector, considering factors such as: (a) the appropriate contribution of sugarcane-based products to the national energy matrix; (b) economic mechanisms for ensuring the sector's self-sufficiency; and (c) scientific and technological development within the industry. CIMA is composed of the Minister of Agriculture and Supply, who presides over the council, alongside the Ministers of Finance, of Development, Industry and Foreign Trade, and of Mines and Energy. While some modifications have occurred over time, this institutional framework remains essentially in place today.

In 2003, aligning with a more flexible fuel market, flex-fuel vehicles were introduced. These vehicles, which are taxed as bioethanol cars, were quickly embraced by consumers. Previously, the choice between bioethanol or gasoline had to be made when purchasing a vehicle. However, flex-fuel technology allows drivers to opt for gasoline (which currently contains 27% anhydrous bioethanol) and/or hydrous bioethanol based on factors such as price, fuel efficiency, performance or availability at the time of refuelling.

Flex-fuel vehicles now account for approximately 85% of Brazil's light vehicle fleet. Their widespread adoption has driven increased domestic demand for hydrous bioethanol, sparking a new phase of expansion for the sugarcane industry. Notably, this technology provides consumers with the flexibility to choose between bioethanol and gasoline whilst also granting bioethanol producers the ability to adjust production based on the relative prices of bioethanol and sugar.

From 2010 onwards, following ANP Resolution 43 of December 2009, ethyl alcohol that meets ANP specifications for fuel purposes began to be referred to as "ethanol". This term is chemically more accurate and aims to distinguish it from alcohol used for other purposes, such as disinfectants or alcoholic beverages. Fuel bioethanol can be either anhydrous, intended for blending with pure gasoline as produced in oil refineries, or hydrous, used as a fuel. Currently, hydrous bioethanol sold in Brazil can be either regular or additive-enhanced, in which case it contains the same detergent and dispersant additives used in gasoline, with its use being optional at the consumer's discretion.

FIGURE 41. VW Gol, the first flex-fuel model, capable of using any mixture of gasoline (E22 or higher) and hydrous bioethanol, launched in 2003

Photo: Volkswagen do Brasil.

FIGURE 42. Since 2010, fuel alcohol has been referred to as ethanol, which can be either regular or additive-enhanced

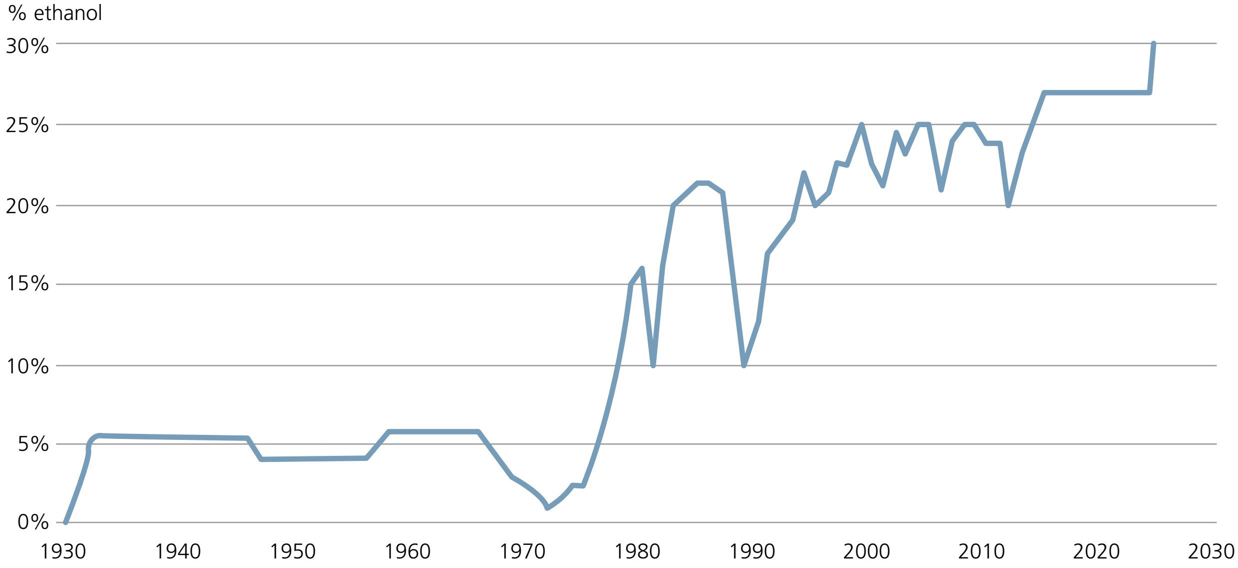
Photo: Harry Wood/Wikimedia Commons/CC-BY-SA-2.0. Available at: https://commons.m.wikimedia.org/wiki/File:Ethanol_fuel_pump_Brazil.jpg. Accessed on: Sep. 2025.

Strengthening the legal framework for biofuels in Brazil and emphasising their contribution to decarbonising the energy sector and promoting sustainable development, the Brazilian government has implemented two major policy measures: the RenovaBio programme, introduced by Law 13,576 of December 2017 (BRASIL, 2017), detailed in Chapter 7, and the Future Fuel Law, as Law 14,993, enacted in October 2024 (BRASIL, 2024a). This law serves as a crucial indicator of public policies aimed at the production and use of biofuels and the reduction of greenhouse gas (GHG) emissions.

Amongst the provisions of the Future Fuel Law, the following stand out: (a) an increase in the ethanol content in gasoline, which must range between 22% and 35%; (b) the establishment of GHG emission reduction targets for airline companies in their domestic operations, with a minimum reduction of 1% starting in 2027 and 10% by 2037; (c) a regulatory framework for carbon capture and storage, with the goal of preventing the emission of 705 million tonnes of CO_2 by 2037; (d) mechanisms and targets to support the production and use of biomethane. This important law is discussed further ahead. Chapter 2 presents the process of effective implementation of E30 in Brazil starting in August 2025, a relevant consequence of the Future Fuel Law.

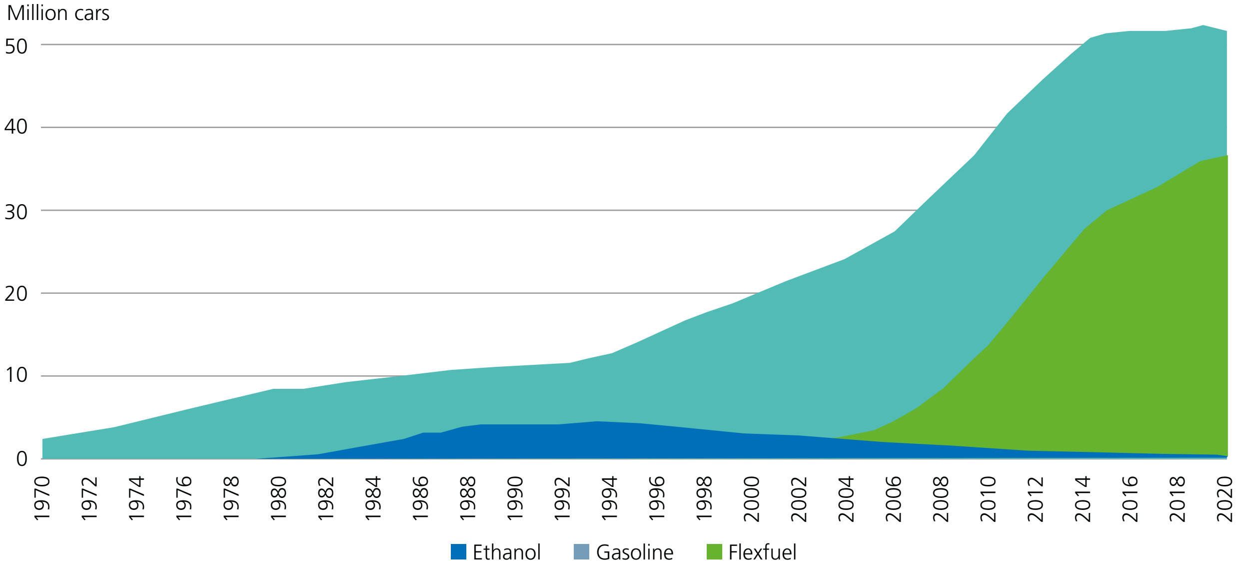
Indeed, Brazil's bioethanol agroindustry has expanded and diversified, consolidating itself economically and presenting positive indicators of environmental sustainability, as will be seen later in this book. A summary of this evolution—from the mandatory adoption of a minimum 5% bioethanol blend in gasoline to the current landscape with its various phases—can be seen in the variation of bioethanol content in gasoline over time (Graph 20, an extension of Graph 13) and in the evolution of the composition of Brazil's light vehicle fleet by fuel type over the past decades (Graph 21). The dominance of flex-fuel vehicles is firmly established in Brazil, with 2023 data indicating that out of a total of 37.3 million automobiles, 85% can run on pure bioethanol.

GRAPH 20. Evolution of anhydrous ethanol content in Brazilian gasoline



Source: Prepared by the authors based on BNDES and CGEE (2008), and EPE (2024a).

GRAPH 21. Evolution of the composition of Brazil's light vehicle fleet by fuel type (1970–2020)



Source: Prepared by the authors based on UNICA (2024).

As Brazil approaches the fifty-year mark since the remarkable increase in bioethanol production and use—initiated by the Proálcool programme, described in previous paragraphs—it is worth discussing the accumulated effects of this productive transformation. In this regard, Nastari (2024) summarised:

> *Between 1975 and 2023, 3.6 billion barrels of oil were replaced with ethanol. This volume represents a saving of more than USD 725 billion (as of December 2023), considering the avoided external debt costs. More than 700,000 direct jobs and over two million indirect jobs were created, and there were significant health and environmental benefits since ethanol is lead- and sulphur-free, does not emit particulate matter and replaces carcinogenic aromatics found in gasoline.* (Nastari, 2024, our translation)

With regard to the significant effect on CO_2 emissions, the volume of gasoline mentioned above indicates that, between 1975 and 2023, 572 billion litres of gasoline were replaced by 818 billion litres of ethanol, assuming equivalent usage efficiency and ethanol having 70% of the calorific value of gasoline. Including the reported demand for 2024 (35.5 billion litres) and the projected demand for 2025 (34.8 billion litres), as presented by the Energy Research Office (EPE, 2024d) in its forecasts for the Brazilian fuel market, it is estimated that approximately 888 billion litres of ethanol will have been consumed in the country over the 50 years of the Proálcool programme. This amount is energetically equivalent to 630 billion litres of gasoline, based on a calorific value ratio of 71%.

Since one litre of gasoline emits 2.75 kg of CO_2 over its life cycle, assuming a calorific value of 31.5 MJ/l, this results in an emission factor of 87.4 gCO_2/MJ (ANP, 2024b). Assuming that ethanol use reduces this emission by around 80%, as will be discussed in the following chapter, a total of 2.20 kg of CO_2 is avoided for each litre of gasoline displaced.

Therefore, over the past fifty years, the use of bioethanol has prevented the emission of an impressive 1.37 billion tonnes of CO_2 in Brazil. The scale of this reduction can be assessed in light of data from the Greenhouse Gas Emissions and Removals Estimation System (SEEG, 2024), which shows that this corresponds to approximately 1.6% of Brazil's total emissions and 10.3% of its energy-related emissions between 1976 and 2022.

This estimate considers only the ethanol fuel produced from the sugarcane agroindustry and does not include electricity generated and exported to the public grid—an aspect that will be addressed in the following chapter, along with its additional positive impacts.

5.2. The ethanol agroindustry in Brazil

Based on a historical overview, the following sections present a comprehensive perspective on the current state of Brazil's bioethanol market. This analysis is provided by EPE, an agency under the Ministry of Mines and Energy, which systematically monitors this market, conducting analyses and projections, and by UNICA, the organisation representing Brazil's sugar and ethanol producers. The scenario is then examined in terms of the productivity and economic competitiveness of bioethanol production in Brazil in recent years through a study conducted by Pecege Institute, an entity that monitors and analyses the Brazilian agricultural products market.

5.2.1. The perspective of the Energy Research Office (EPE)

> *This section reproduces Technical Note NE-EPE-DPG-SDB-2024-41 from September 2024, authored by Angela Oliveira da Costa, Marina Ribeiro, Rachel Henriques, and Rafael Araujo of the Petroleum Derivatives and Biofuels Department of the Energy Research Office (EPE), prepared for this book.*

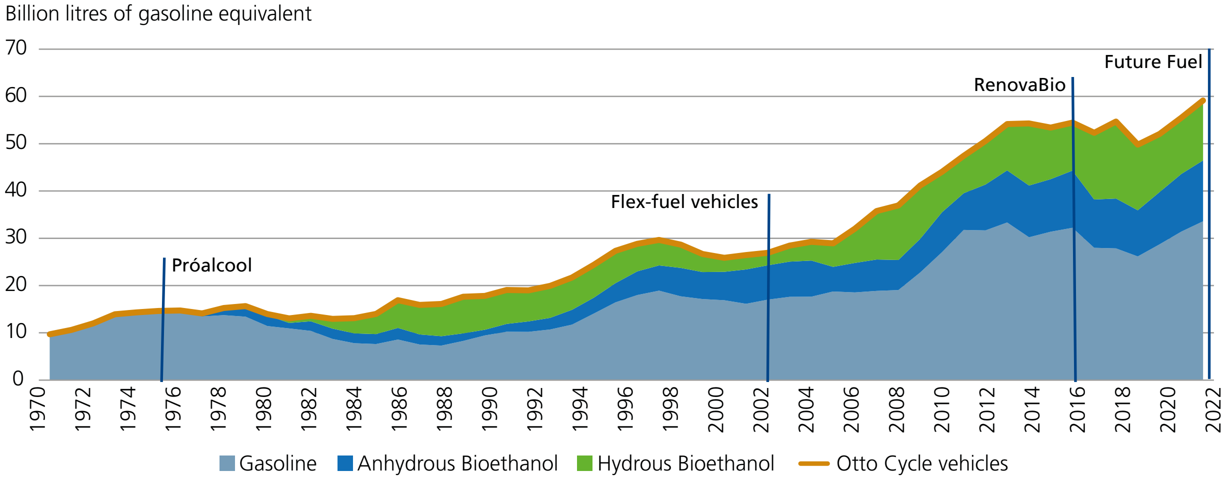
Brazil is one of the world's leading biofuel producers, a position achieved due to its favourable soil and climate conditions and various public policies that have encouraged an increasing share of biofuels in the national energy mix. These policies include mandatory biofuel blending (bioethanol and biodiesel) with petroleum derivatives, tax differentiation mechanisms between renewable and fossil fuels, specific financing lines and, more recently, Law 13,576/2017, which established the National Biofuels Policy (RenovaBio), and Law 14,993/2024, the Future Fuel Law (BRASIL, 2017, 2024; EPE, 2016, 2023a, 2023b).

The Future Fuel initiative consolidates existing public policies whilst introducing new measures such as the National Programme for Sustainable Aviation Fuel (ProBioQAV), the National Green Diesel Programme (PNDV), and the National Programme for the Decarbonisation of Natural Gas Producers and Importers and the Promotion of Biomethane. It also proposes adjustments to the anhydrous ethanol content in gasoline C and the biodiesel content in diesel B.

Gasoline C and diesel B are designations used by Brazilian government agencies regulating the fuel market. These refer to blends of petroleum-derived fuels with biofuels: gasoline mixed with anhydrous ethanol and diesel blended with biodiesel in proportions set by the federal government, aligning with energy and environmental policies and adhering to ANP specifications.

The demand for biofuels in Brazil is primarily driven by the transport sector. Graph 22 illustrates the evolution of fuel consumption in Otto cycle vehicles[2], including hydrous bioethanol and gasoline C (anhydrous bioethanol and gasoline), expressed in gasoline-equivalent volume. This graph highlights key public policies over time: Proálcool in 1975, the introduction of flex-fuel vehicles in 2003, RenovaBio in 2017 and Future Fuel in 2024. Over this period, ethanol's share in the light vehicle fleet's fuel demand, measured in gasoline equivalents, grew significantly from 1% in 1975 to 38% in 2004, reaching 43% in 2023 (EPE, 2024a).

GRAPH 22. Fuels consumption by Otto cycle vehicles in Brazil (1970–2023)



Source: EPE (2024a).

Bioethanol production in Brazil is predominantly derived from sugarcane, but in recent years, maize has emerged as a significant feedstock. As shown in Graph 23, numerous sugarcane-processing plants started operations between 2005 and 2010. However, several ceased operations by 2017. Since

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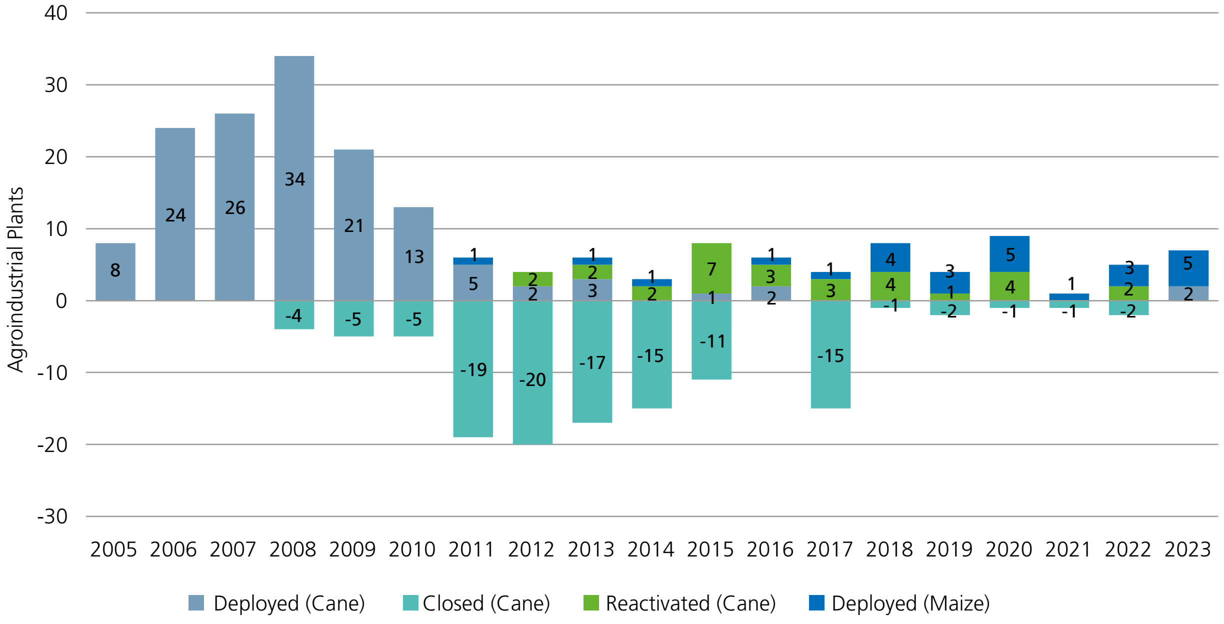
[2] Otto cycle vehicles are powered by spark-ignition internal combustion engines, commonly used in cars and motorcycles.

then, some facilities have been reactivated, though new developments have been limited.

It is estimated that the nominal sugarcane crushing capacity increased by approximately 166 million tonnes over this period. Currently, Brazil's nominal sugarcane processing capacity stands at around 870 million tonnes, with 360 plants (including those processing both sugarcane and maize) and an estimated nominal biofuel production capacity of 48 billion litres (MAPA, 2023).

Since 2011, maize-based ethanol plants have begun operating, gaining prominence from 2018 onwards. As of 2023, there were 24 operational units (13 exclusively processing maize and 11 flexible plants processing both sugarcane and maize), with a total annual maize processing capacity of 18.3 million tonnes and ethanol production of 7.1 billion litres. Additional projects exploring other cereals, such as wheat and soybeans, are under consideration, with three plants in the study or implementation phase (MAPA, 2023). These facilities are included in Graph 23 alongside maize-processing plants.

GRAPH 23. Entry and exit of ethanol production plants in Brazil (2005–2023)

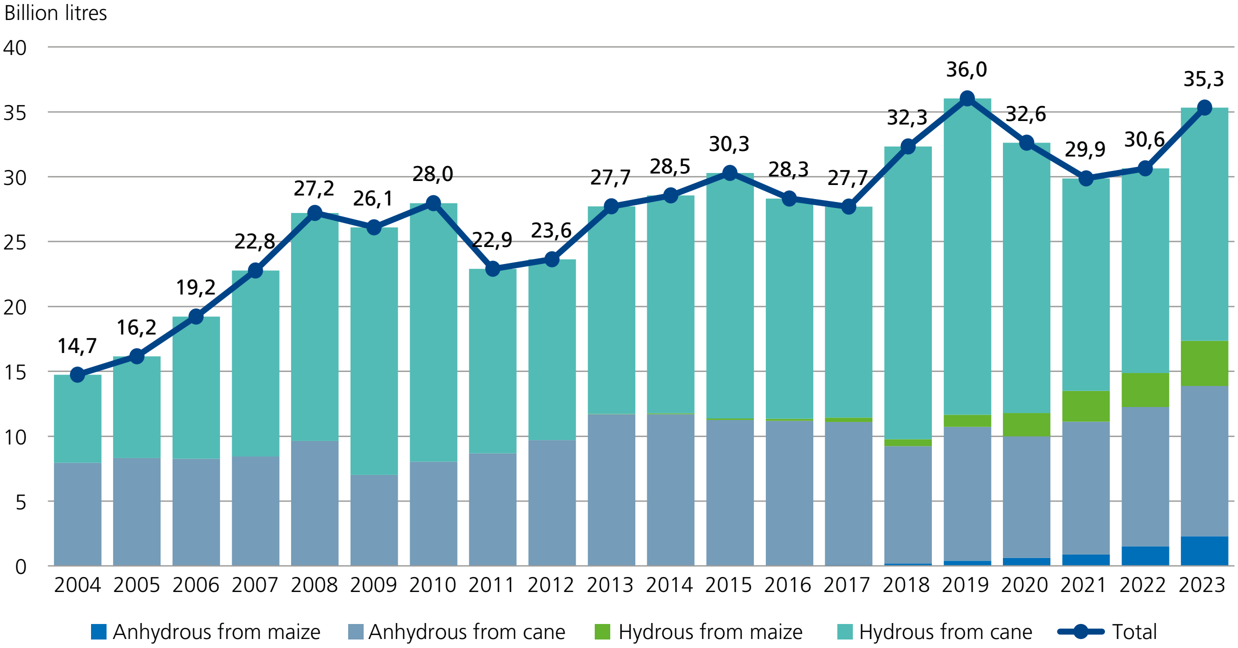


Source: EPE based on MAPA (2023) and UNICA (2014).

Beyond ethanol, the sugar-energy sector also plays a key role in sugar production, holding the leading position in the international market with over 40% of global exports, a share maintained over the past decade. Production has increased from 26 million tonnes in 2004 to 46 million tonnes in 2023. Bioelectricity represents another major revenue stream for the sector, with advancements in biogas production from vinasse, filter cake and, to a lesser extent, straw and sugarcane tops (EPE, 2023b).

Ethanol production from maize has grown substantially, especially in the Central-West region. As discussed in Chapter 3, this technological pathway benefits from the increasing maize supply, which, unlike sugarcane, allows for a second or even a third annual harvest when combined with other crops such as soybeans. Additionally, maize ethanol production generates valuable by-products such as maize oil for human consumption and dried distillers grains with solubles (DDGS) for animal feed, further diversifying plant revenues (IMEA, 2017; Milanez *et al.*, 2014). Another advantage of maize is its storability, enabling year-round plant operation. In 2023, Brazil's ethanol production (anhydrous and hydrous) from sugarcane and maize totalled 35.3 billion litres, with maize accounting for 15% of this volume.

GRAPH 24. Evolution of ethanol production in Brazil by feedstock type (2005–2023)



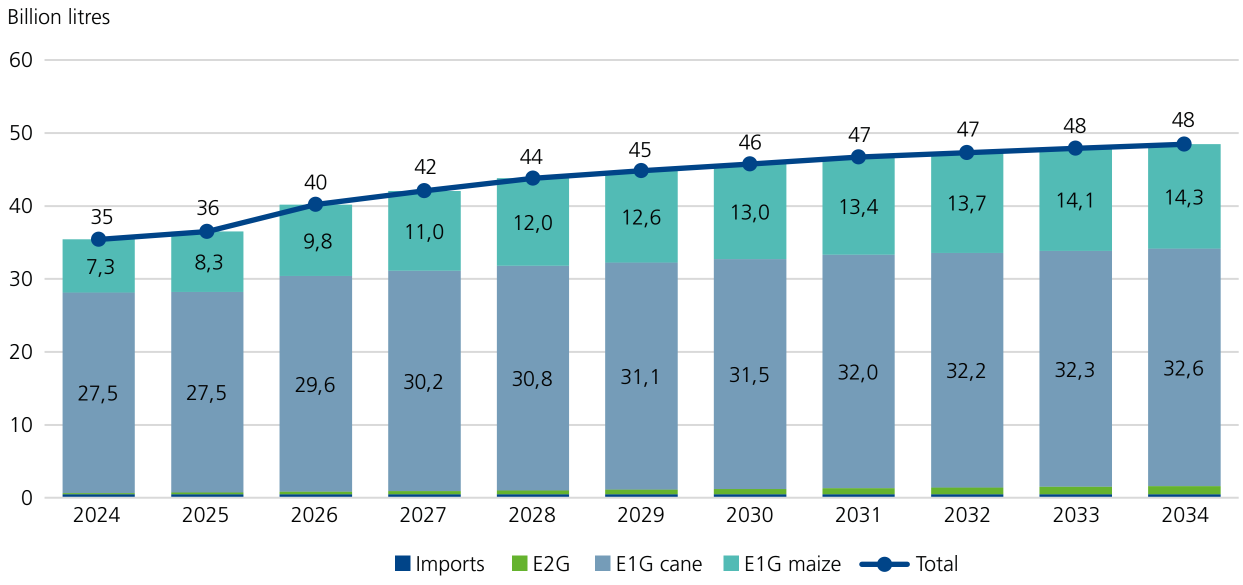
Source: EPE based on MAPA (2024) and UNICA (2024).

By the end of 2024, RenovaBio will have completed five years of full implementation, with the sale of decarbonisation credits (CBIOs), providing additional revenue to the sector and incentivising efficiency improvements by reducing carbon intensity (gCO_2/MJ) in transport fuels. This important topic is further discussed in Chapter 7 on the sustainability of bioethanol.

The transition to a sustainable, low-carbon economy aimed at mitigating the adverse effects of human activity on the climate and protecting quality of life on the planet necessitates a greater use of renewable energy sources produced at scale and in an economically viable manner alongside improvements in energy efficiency. In this context, biofuels are one of the key drivers in overcoming this challenge, particularly in Brazil, which benefits from favourable soil and climate conditions, as well as existing infrastructure.

For the period from 2024 to 2034, ethanol supply is projected to grow by more than 3% per year, with sugarcane maintaining its importance whilst maize ethanol experiences significant expansion, potentially accounting for 30% of bioethanol production by the end of the period. Production plants will also be able to harness their potential for biogas production, second-generation ethanol, sustainable aviation fuel (SAF) and other renewable fuels. Hydrous ethanol is expected to become more competitive relative to gasoline C. Graph 25 summarises this evolution, including forecasts for lignocellulosic bioethanol (E2G) production and potential bioethanol imports, which could represent 2% and 1% of total ethanol supply, respectively, in 2034.

GRAPH 25. Projection of ethanol production in Brazil by feedstock (2024–2034)



Source: EPE (2024b).

Like ethanol, other biofuels are expected to maintain a significant role in Brazil's national energy mix in the future. Over the next decade, production of other biofuels is anticipated to increase, with a greater diversity of feedstocks, including hydrotreated vegetable oil (HVO) and synthetic fuels derived from biomass, further strengthening Brazil's position as a producer of low-carbon fuels.

Public policies related to this sector, such as RenovaBio and the Future Fuel Law, reinforce the positive impacts and the continued development of the industry. The National Biodiesel Production and Use Programme (PNPB) has proven to be a key public policy for integrating family farming into the formal economy, contributing to the production of a substantial share of the basic food basket consumed by Brazilians. After two decades of success, a remaining challenge is to further diversify feedstocks and promote regional development. To address this, new mandates have recently been introduced to incorporate inputs from the Northeast and Semi-Arid regions (BRASIL, 2024a).

In the context of Brazil's G20 Presidency, President Lula outlined three overarching priorities: "the fight against hunger, poverty and inequality; the three dimensions of sustainable development (economic, social and environmental); and reform of global governance" (BRASIL, 2024b). The PNPB model, which can be replicated not only for new biofuels but also for other sectors, has provided the foundation for renewable fuel production to become a key instrument in achieving Brazil's priority objectives. It serves as a powerful driver for strengthening family farming and enhancing food security.

To ensure alignment between biofuel production and these established priorities, efforts must be directed towards ensuring that biomass production generates the desired positive impacts for Brazilian society. In this way, Brazil is expected to maintain its relevance in renewable energy use and its leadership in a fair and inclusive global energy transition, contributing to greenhouse gas emission reduction targets while also attracting investment.

5.2.2. The perspective of ethanol producers

This section reproduces the note A agroindústria da bioenergia no Brasil *(The bioenergy agribusiness in Brazil), published in August 2024, authored by Luciano Rodrigues, Lucas Rodrigues, and José*

Guilherme Belon from the Sectoral Intelligence Directorate of Brazilian Sugarcane and Bioenergy Industry Association (UNICA), prepared specifically for this book. The mills affiliated with UNICA account for over 54% of the country's sugarcane production, 60% of ethanol production—including more than 85% of maize ethanol—54% of sugar production and nearly 79% of the bioelectricity supplied to the National Interconnected System (UNICA, 2024).

Throughout history, successful organisations and industries have been those capable of redefining their value to society in response to constant and increasingly intense changes in the business environment.

This dynamic has shaped the history of Brazil's sugar-energy sector. It is an industry whose origins date back nearly 500 years to sugar production, but it has since evolved far beyond the traditional role of agriculture as a food source. Over recent decades, the sector has established itself as the country's primary renewable energy source, currently accounting for nearly 20% of Brazil's total domestic energy supply (EPE, 2024a).

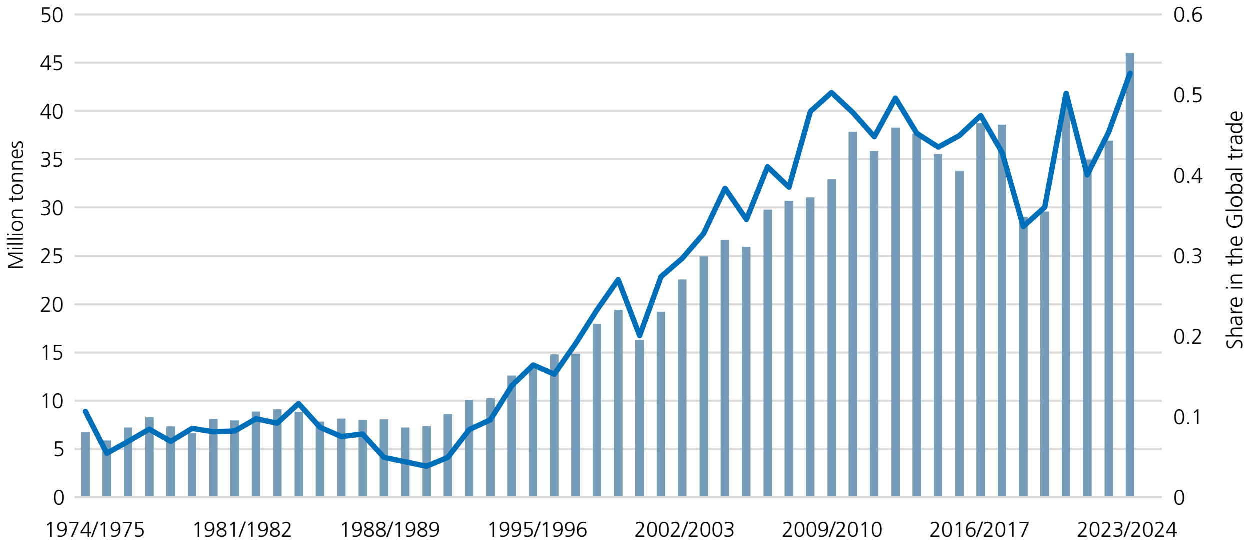
This transformation began with ethanol produced from sugarcane. The biofuel was first blended with gasoline in 1931 and gained prominence in the 1970s when the Brazilian government sought to diversify its energy sources in response to global oil market shocks. This initiative led to a surge in ethanol production, the development of ethanol-powered vehicles and the establishment of nationwide distribution infrastructure for the biofuel.

Following an extended period of State intervention in the sector, a new cycle of ethanol production expansion began in 2003, when the industry was already operating in a free-market environment. This growth was driven by the introduction of flex-fuel vehicles, a technological innovation that allowed Brazilian consumers for the first time to choose their fuel mix at every refuelling—whether ethanol, gasoline or any combination of the two.

This development, combined with the widespread availability of ethanol in the domestic market, has since resulted in a reduction of over 650 million tonnes of CO_2equivalent greenhouse gas (GHG) emissions and savings of more than BRL 80 billion for Brazilian consumers (UNICA, 2024). By 2023, a fleet of 37 million cars and 14 million motorcycles capable of running on ethanol ensured that biofuel accounted for 45% of the light vehicle fuel mix in Brazil (ANP, 2024d).

The growth in ethanol production has been achieved without compromising the rational use of natural resources or food production. As illustrated in Graph 26, the sector exports more than 70% of its sugar output and supplies nearly 50% of the global sugar market, maintaining Brazil's position as the most significant supplier of the product worldwide (USDA, 2024; MAPA, 2023). Additionally, ethanol production occupies approximately 6 million hectares of sugarcane plantations and fewer than 3 million hectares of second-crop maize, meaning that only around 1% of Brazil's land area is dedicated exclusively to biofuel production (IBGE, 2024; UNICA, 2024).

GRAPH 26. Evolution of sugar production in Brazil from the 1974/1975 harvest to the 2023/2024 harvest



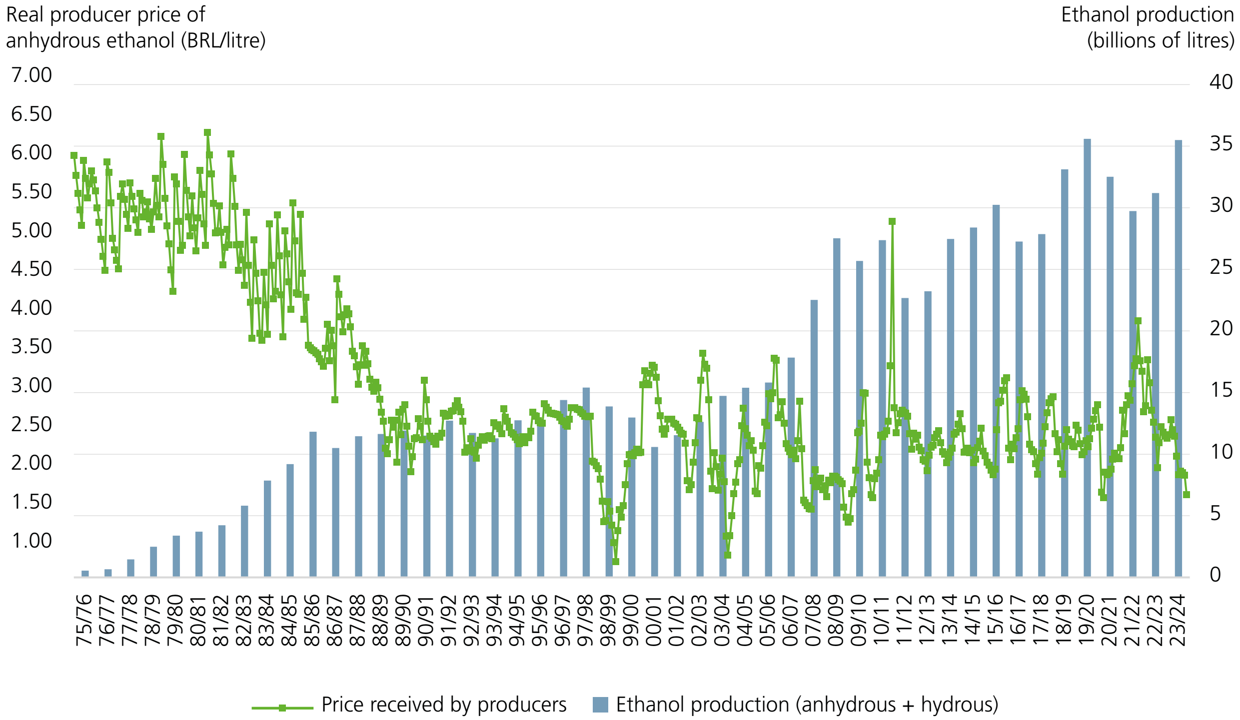
Source: Prepared by the authors based on data from MAPA (2024) and USDA (2024).

Concerns about land-use change are explicitly addressed in the eligibility criteria of Brazil's National Biofuels Policy (RenovaBio). The regulation establishes a cut-off point, excluding from the programme any property that converts native vegetation to produce energy feedstock. This measure goes beyond existing environmental legislation, setting strict traceability requirements and a zero-deforestation rule for biomass supplied to biofuel production in the country. Compliance with this rule is monitored by production units, audited by external firms and validated by the National Agency for Petroleum, Natural Gas and Biofuels (ANP).

The sector's expansion has also been accompanied by efficiency gains, leading to a real reduction in ethanol prices over the past decades. As illustrated in

Graph 27, since the launch of Brazil's ethanol programme in the 1970s, the actual price of ethanol received by mills has halved, while biofuel production has grown exponentially. The prices shown in this graph are expressed in December 2023 values, adjusted using the IGP-DI deflator.

GRAPH 27. Prices of anhydrous ethanol sold by producers and the evolution of Brazilian bioethanol production

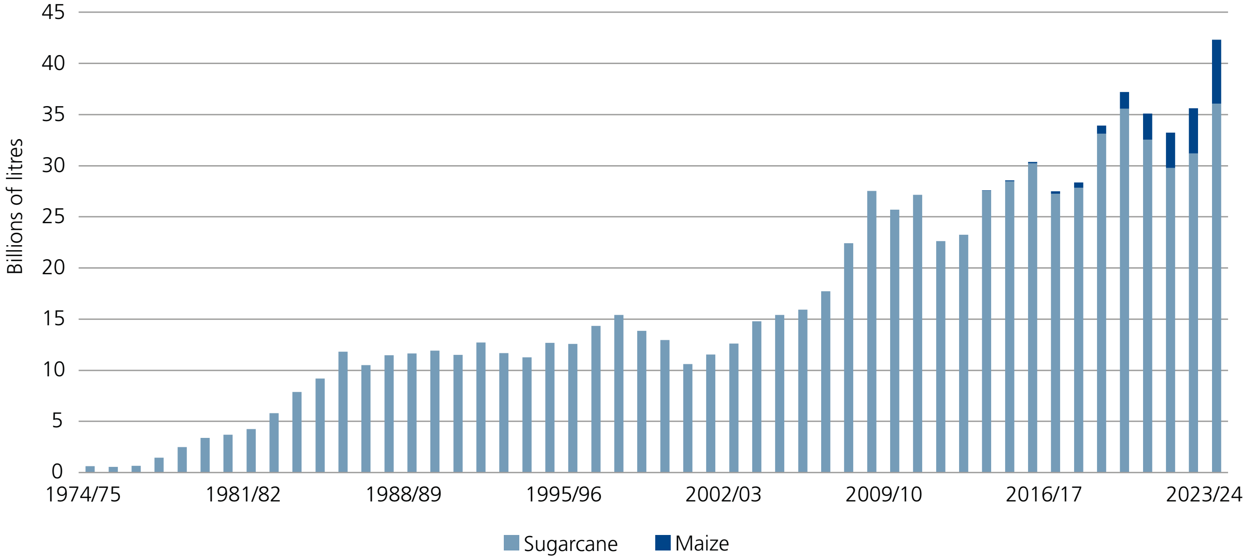


Source: Prepared by the authors based on data from UNICA (2024), MAPA (2024), and EPE (2024a).

Beyond changes in production systems and efficiency improvements, recent transformations in the sector have included the diversification of energy products and the expansion of raw materials used in bioenergy production.

Over the past decade, maize-based ethanol has firmly established itself in the Brazilian market, particularly in the Central-West states. In the 2013/2014 harvest, just 37 million litres of maize ethanol were produced from two processing units. By the 2023/2024 cycle, production had surged to 6.27 billion litres, with 18 mills in operation, including flexible plants capable of processing both sugarcane and second-crop maize (UNICA, 2024). As shown in Graph 28, by the 2023/2024 cycle, maize ethanol accounted for 17% of Brazil's total ethanol production.

GRAPH 28. Evolution of ethanol production in Brazil by feedstock from the 1974/1975 harvest to the 2023/2024 harvest



Source: Prepared by the authors based on data from MAPA (2024).

This growth is driven by Brazil's unique competitive advantage—its abundant arable land and favourable climate, which allow for crop rotation throughout the year. These conditions enable the cultivation of second-crop maize (or winter maize), which takes advantage of farmland previously used for soybean production in the summer, enabling a second harvest within the same agricultural calendar. Currently, second-crop maize covers just over 50% of the soybean-growing area in the region, highlighting the potential for further expansion without the need for additional farmland (CONAB, 2024a).

In addition to optimising soybean-growing areas, maize ethanol plants in Brazil utilise biomass to generate the electricity and steam required for ethanol production, ensuring that the carbon intensity of maize ethanol is comparable to that of sugarcane ethanol. On the industrial front, ethanol mills are increasingly harnessing solar energy from agricultural fields and expanding the range of products derived from the same biomass supplied by farms.

A notable example is the production of bioelectricity from the combustion of sugarcane bagasse. Over the past decade, the sector has generated 35 TWh annually, exporting approximately 60% of this to the national grid (UNICA, 2024). In 2023, this accounted for 3.4% of Brazil's total electricity generation and nearly 75% of the country's renewable biomass energy supply (UNICA, 2024).

Another promising area in electricity generation is biogas, produced from ethanol and sugar by-products such as vinasse and filter cake—an exemplary case of the circular economy. Beyond electricity generation, purified biogas can be converted into biomethane, which can replace natural gas or even diesel in vehicle transport.

Estimates suggest that Brazil has the potential to produce 10.87 billion Nm^3 of biogas per year in the short term—equivalent to nearly 5% of the country's electricity consumption or around 12% of its diesel demand (BEP, 2021). More than 70% of this potential comes from using vinasse and filter cake within the sugar-energy sector.

As part of the sector's transformation, sugarcane biomass is also being used to produce second-generation ethanol (2G ethanol). Brazil is home to the world's largest 2G ethanol plant, with an installed production capacity exceeding 100 million litres per year, alongside ongoing investments in new industrial facilities.

Innovations in the production system also include: (i) advancements in integrated pest and disease management for sugarcane, such as increased use of biological agents and enhanced natural pest control through greater landscape biodiversity; (ii) improved internal logistics within companies; (iii) adoption of precision agriculture tools and artificial intelligence for crop monitoring and digitalisation of operations; (iv) development of crop varieties better suited to production systems, including genetic engineering techniques; (v) deployment of innovative planting methods, such as pre-sprouted seedlings and research into the breakthrough technology of artificial sugarcane seeds; (vi) new cultivation techniques aimed at increasing soil carbon retention, amongst others.

In the coming years, the sector is also expected to incorporate renewable hydrogen production from ethanol, as well as the production of sustainable aviation fuel (SAF) and marine biofuels using raw materials supplied by the sugar-energy industry.

Alongside these technological advancements, Brazil has also made significant institutional progress in recent years. The stabilisation of domestic petroleum product pricing rules and, more importantly, the approval of the National Biofuels Policy (RenovaBio) in 2017 marked major milestones in this regard. The programme's primary goal is to reduce greenhouse gas (GHG) emissions in Brazil's transport sector by replacing fossil fuels with biofuels such as RenovaBio-certified companies, with carbon intensity levels audited by external firms and the ANP.[3]

Looking ahead, the future of the sugar-energy sector will require stronger communication efforts to debunk misconceptions and present Brazil's unique bioenergy model to diverse global audiences in a technically sound and accessible manner.

On the global stage of the energy transition, Brazil lacks the financial resources of some nations that offer substantial economic incentives to expand clean energy production. However, in the bioenergy sector, the country enjoys extensive experience, mastery of production processes, and exceptional conditions for highly efficient biofuel manufacturing. Furthermore, Brazil has been improving its institutional environment to attract new investments and foster a thriving bioenergy market.

Through a combination of government initiatives, private-sector collaboration and a strategic approach to balancing competing interests, Brazil is well-positioned to maintain bioenergy as a key solution—not only for providing affordable food but also for low-carbon energy production in the years to come.

5.3. Productivity, technological innovations and margins in ethanol production in Brazil

This section reproduces the note of the same title, dated November 2024, prepared for this book by Haroldo Torres, Managing Partner at Pecege Consultoria e Projetos, a company specialising in economic and comparative analyses, forecasts and other tools for understanding the sugar-energy sector.

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[3] In addition to RenovaBio, the authors of this note discuss and endorse other government programmes aimed at promoting energy efficiency and emissions reduction, particularly those involving bioethanol. However, as these topics are explored in greater depth in other chapters of this book, they have been omitted by the editors.

In 1975, in response to the oil shock two years earlier, Brazil launched the National Alcohol Programme. Known as Proálcool, it was one of the first initiatives aimed at promoting an alternative to petroleum-based fuels in motor vehicles, with a clear focus on alcohol derived from sugarcane. Although Proálcool initially achieved success, over time ethanol-powered cars lost their appeal. Consumers were concerned about the availability and price of what was then referred to as an "alternative" fuel. These concerns were justified by the characteristics of sugarcane production: seasonal and subject to price fluctuations in the global sugar market, which could incentivise diversion towards sugar production during price spikes.

With the introduction of flex-fuel engines in 2003, ethanol regained its attractiveness as its use was no longer tied to the consumer's vehicle purchase decision—an investment typically significant for Brazilian buyers. The success of these vehicles is evident from data 20 years later: according to ANFAVEA (2024), in 2023, 83.0% of the 2.2 million newly registered cars and light commercial vehicles were flex-fuel, capable of running on both ethanol and gasoline. With a broader base of potential consumers, ethanol's market penetration in the Otto cycle segment became primarily a classic market-driven issue shaped by consumer preferences and its price competitiveness relative to gasoline (gasoline C).

Regarding the choice between gasoline and ethanol, a convention emerged in the early years of flex-fuel vehicles that ethanol should only be preferred if its price was less than 70% of that of gasoline due to differences in energy content. However, given the current composition of gasoline sold at filling stations, in purely calorific terms, this equivalence now stands at 71.9%, not accounting for variations between different flex-fuel vehicle designs.

Beyond purely market-driven factors, ethanol became a key component of Brazil's green economy strategy in the early 2000s. In this shift, even the terminology associated with the sector evolved. What was previously referred to as "alcohol" and considered an "alternative fuel" became known as "ethanol," categorised as a "biofuel," highlighting the specific type of alcohol produced in Brazil and its renewable nature.

In a later stage, particularly in the 2010s, growing concerns over climate change—culminating in the Paris Agreement—spurred the adoption of various measures to reduce greenhouse gas (GHG) emissions. Under this agreement, Brazil committed to reducing emissions by 37% by 2025 and by 43% by 2030 relative to 2005 levels (BRASIL, 2024a). Given Brazil's unique fuel market, biofuels assumed a vital role in the country's commitments under the Paris Agreement.

The significance of biofuels in Brazil's climate commitments was further reinforced in 2017 with the introduction of the National Biofuels Policy, commonly known as RenovaBio. This policy aimed to encourage biofuel production and consumption, primarily through the creation of a carbon credit market. This mechanism was designed to shift economic incentives along the fuel production and distribution chain in favour of sustainable alternatives, complementing existing policies such as tax differentiation and mandatory blending mandates.

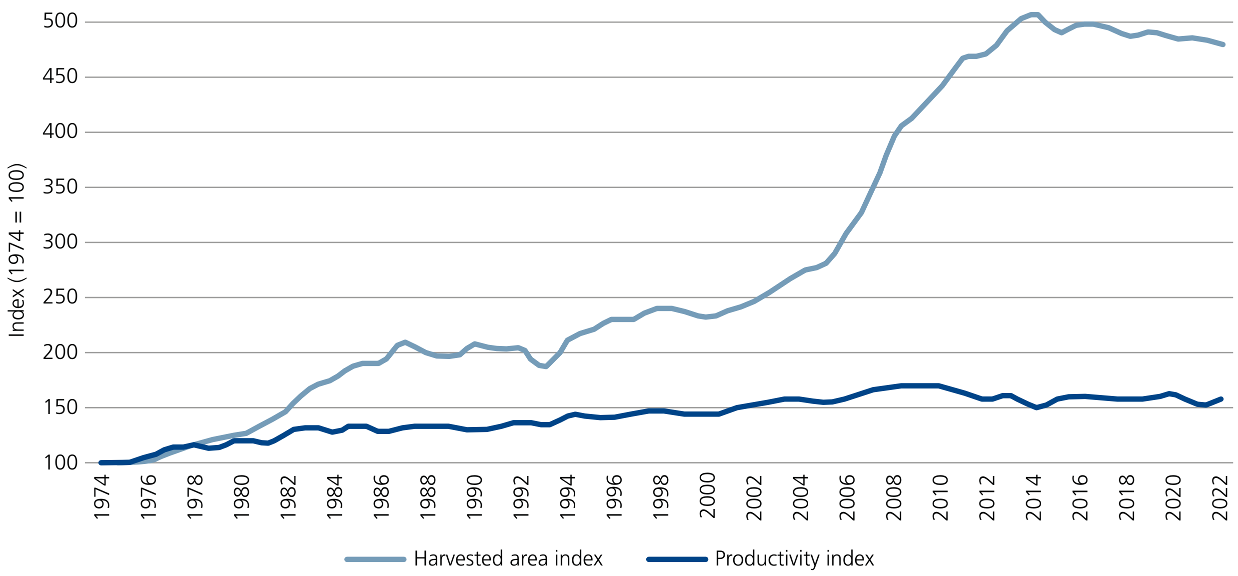
Although maize-derived ethanol now accounts for approximately 16% of national biofuel production (EPE, 2024a), sugarcane and its entire supply chain remain crucial both in public policy and in fulfilling Brazil's international commitments. This justifies the particular emphasis of this section on sugarcane-based ethanol.

5.3.1. Evolution of sugarcane productivity

Despite the significance of sugarcane-based ethanol in Brazil's domestic and international policies, it is important to emphasise that the sugar-energy sector is predominantly composed of private enterprises that primarily seek to serve the interests of their shareholders. Since its liberalisation in the 1990s, the industry has operated without production quotas or price controls. Given that the same raw material is used for two distinct products, ethanol production must be analysed within the broader context of the sugar-energy business, which necessarily includes sugar production.

The overall output of the sugar-energy sector (comprising both sugar and ethanol) depends on the availability of raw materials, which in turn is influenced by the expansion of cultivated land and agricultural productivity. Although, particularly in the 2000s, increases in cultivation area accounted for most of the growth in sugarcane production, productivity has played a crucial role in the long term. This trend is illustrated in Graph 29, which presents an index (1974 = 100) for harvested area and agricultural productivity.

GRAPH 29. Indices of harvested area and sugarcane productivity (1974–2022)



Source: Prepared by the authors based on IBGE (2024).

Regarding long-term productivity trends, genetic improvement has played a key role. Although sugarcane breeding presents greater challenges compared to other major agricultural crops, considerable progress has been made, particularly since the 1970s. This progress has been driven by initiatives such as those undertaken by Copersucar—through the Sugarcane Technology Centre (CTC)—and the National Sugarcane Breeding Programme (Planalsucar), which later evolved into the Interuniversity Network for the Development of the Sugar Energy Sector (RIDESA). Before these initiatives, the Agronomic Institute (IAC) was already active in the sector. The development of new sugarcane varieties contributed to a 72.6% increase in Brazil's average sugarcane productivity between 1974 and 2009, as illustrated in Graph 29.

Another factor contributing to productivity gains during this period was the introduction of vinasse application in fields from the 1980s onwards. Initially regarded as a significant environmental liability, vinasse—produced in large quantities during ethanol distillation—was discharged directly into water bodies until the 1960s and later into designated "sacrifice areas" during the 1970s (Rossetto, 2022).

The application of vinasse in agricultural fields provided at least three key benefits: ensuring an environmentally responsible disposal method for industrial waste, supplying additional soil moisture and partially supplementing plant nutrition. The success of vinasse application was so remarkable that, over time, it became a valuable asset for sugar mills, even serving as a bargaining tool in sugarcane purchasing agreements with suppliers. More recently, vinasse has been used as a substrate for producing essential agricultural inputs, such as fertilisers and pesticides, and has shown potential as a feedstock for biogas and/or biomethane production—a sustainable alternative to natural gas.

In the 2000s, particularly in the Centre-South region[4], regulations limiting the burning of sugarcane fields prompted a widespread mechanisation of field operations, especially in harvesting and transportation. At least in São Paulo State, there is no evidence that mechanisation has had a significant impact on agricultural productivity (Castro *et al.*, 2022). However, the practice significantly enhanced the environmental sustainability of the sector, as evidenced by a 72.8% reduction in sugarcane burning emissions at the national level between 2010 and 2016 (MCTI, 2021). Additionally, mechanisation increased the availability of biomass for cogeneration as it enabled the processing of sugarcane straw.

Nevertheless, from the 2010s onwards, sugarcane productivity stabilised. This trend has been attributed to factors such as the expansion of cultivation into new areas lacking specifically adapted sugarcane varieties (Garofalo *et al.*, 2020), the ageing of sugarcane fields and reductions in technological investment in certain regions CONAB, 2024). Research and development (R&D) efforts in sugarcane breeding also face additional challenges due to the crop's long lifecycle—once planted, sugarcane can be harvested five or more times—which makes the validation of modern technologies a slow process. In terms of adoption, during periods of industry expansion, producers may have no choice but to rely on pre-existing varieties. When new varieties are introduced, they can only be fully implemented once older plantations are replaced.

At the same time, the debt cycles experienced by the sector during the 2010s—resulting from low ethanol prices—contributed to reduced investment in both

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[4] The Centre-South (*Centro-Sul*) of Brazil is a socioeconomic concept, not an official division, encompassing São Paulo, Paraná, Santa Catarina, Rio Grande do Sul, Minas Gerais, Mato Grosso do Sul, and parts of Goiás and Mato Grosso, where most of the nation's agriculture and industry are concentrated.

biological assets and technological advancements. This lack of investment has kept agricultural productivity stagnant.

5.3.2. Price and cost dynamics of bioethanol

The stagnation in agricultural productivity has posed additional challenges to cost management within the sector, particularly for ethanol production. Historically, raw materials have accounted for the majority of agro-industrial production costs. Over the past five harvest seasons, raw materials—including depreciation of the agricultural phase—have represented an average of 79.4% of the total operational cost of hydrous ethanol, as shown in Table 13.

TABLE 13. Composition of agro-industrial ethanol production costs (in BRL/m³ at current prices)

INDICATORS/HARVESTS	19/20	20/21	21/22	22/23	23/24	% CTA*
Cash cost of raw materials	1,224.95	1,089.50	1,689.22	2,017.99	1,886.49	77.8%
Depreciation of agricultural phase	23.12	25.86	30.87	34.34	47.10	1.6%
Industrial processing cost	128.31	144.98	219.91	228.87	234.85	9.4%
Industrial labour	44.72	47.33	58.48	68.70	77.65	3.0%
Industrial inputs	33.40	36.04	60.11	68.53	72.07	2.6%
Chemicals	17.62	21.81	34.01	36.21	40.73	1.5%
Fuels and lubricants	1.98	2.78	2.96	4.42	4.81	0.2%
Packaging	0.00	0.00	0.00	0.00	0.00	0.0%
Electricity	13.79	11.45	23.15	27.90	26.54	1.0%
Industrial maintenance	29.37	39.38	41.51	69.15	59.68	2.3%
Materials	17.71	21.85	24.43	41.72	36.16	1.4%
Third-party services	11.65	17.53	17.08	27.43	23.52	1.0%
Industrial expenses	13.36	17.54	19.68	16.89	18.69	0.9%
Outsourced services	3.55	3.60	8.68	8.15	6.21	0.3%
Industrial administration	9.81	13.94	10.99	8.74	12.48	0.6%
Other industrial costs	7.47	4.69	40.14	5.60	6.76	0.6%
Depreciation of industrial phase	6.76	47.00	68.11	60.13	62.26	2.3%
Sales, general and administrative expenses (SG&A)	102.74	151.08	216.46	278.51	156.39	8.8%
Cash cost of agro-industrial production (CCA)	1,456.00	1,385.56	2,125.59	2,525.37	2,277.73	96.1%
Total agro-industrial cost (CTA)	1,485.88	1,458.42	2,224.57	2,619.84	2,387.09	100.0%

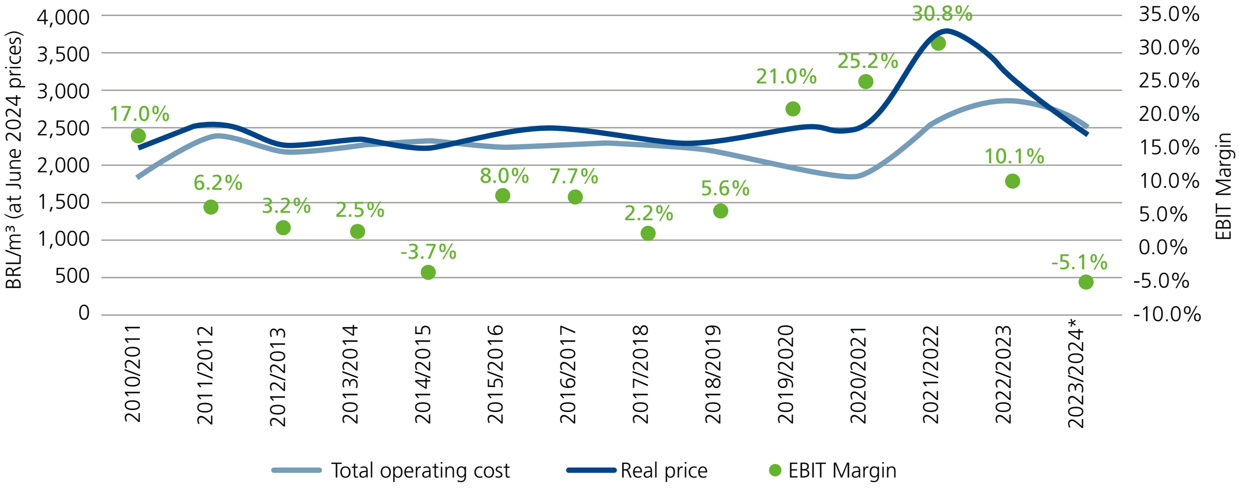
*% CTA = Percentage of total agricultural cost, five-season average.

Source: Prepared by the authors based on Pecege Consultoria e Projetos (2024).

Since the majority of ethanol production costs are linked to raw materials—similar to much of Brazilian agribusiness—its production is highly dependent on global supply chains for agricultural and industrial inputs. As a result, sugarcane-derived biofuel is significantly exposed to several types of global crises, as well as exchange rate fluctuations, which cannot be offset by exports due to the relatively small volume involved.

As actual costs remained relatively stable throughout the 2010s, as shown in Graph 30, the key factor determining the attractiveness of ethanol production has been its selling price, which is formed in the domestic market and primarily influenced by fluctuations in gasoline prices.

GRAPH 30. Total operating cost, price received and EBIT margin in hydrous bioethanol production in Brazil



*The 2023/2024 harvest in the North and Northeast regions was still ongoing when the graph was produced.
Source: Prepared by the authors based on Pecege Consultoria e Projetos (2024) and CEPEA/USP (2024).

This relationship is clearly reflected in the dynamics of margins for hydrous ethanol production and sales in Brazil, as illustrated in Graph 30. The graph presents data for the 14 most recent harvests, including the net price received, ethanol production costs—both adjusted for inflation to June 2024 prices using the IPCA as a deflator—, as well as the corresponding Earnings Before Interest and Taxes (EBIT) margin.

Even before accounting for financial expenses and corporate income tax, the average margin over these harvests remained below 10%, turning negative in 2014/2015 and 2023/2024. Given the characteristics of the sector, such a margin would be insufficient to provide the level of capital returns required by investors.

On the cost side, the most significant deviation from historical patterns occurred after the COVID-19 pandemic. While key global commodity prices initially dropped sharply, the disruption of multiple global supply chains and the depreciation of the Brazilian currency exerted substantial upward pressure on costs. Despite this, ethanol producers benefited from improved margins due to higher international oil prices and increased domestic petrol prices, reinforcing the role of price levels in the sector's attractiveness.

However, this favourable scenario ended due to a combination of changes in federal and state taxation, and in the 2023/2024 harvest, an increase in raw material supply led to lower prices and a negative EBIT margin.

Monitoring margins from ethanol production and subsequent sales by sugar-energy mills is crucial for any policies that involve or depend on private-sector decisions regarding the production mix of these mills. While some ethanol production occurs regardless of direct profitability comparisons with sugar—either in dedicated distilleries or through indirect production from final molasses distillation—, the absence of profitability in the biofuel sector could jeopardise public policies reliant on it.

5.3.3. The importance of agricultural productivity

Although agricultural productivity has stagnated from the 2010s onwards—due to the inherently slow progress of sugarcane genetic improvement research and a cycle of debt driven by unfavourable price conditions—, it played a crucial role in the development of Brazil's sugar-energy sector. This productivity growth resulted from a series of innovations that not only enhanced yields but also strengthened the sustainability of sugar-energy production, particularly in relation to bioethanol.

Given bioethanol's importance in Brazil's greenhouse gas emission reduction commitments, including international agreements, the economic viability of its production is paramount. Without sustained profitability, key environmental policies could become unfeasible. In this context, improvements in agricultural productivity are essential for determining sector margins, and investment in new sugarcane varieties—better suited to the regions where the sector is expanding—is indispensable for long-term profitability.

At the same time, innovations that enhance the environmental sustainability of the agro-energy sector are vital to reinforcing bioethanol as a viable alternative in the energy transition. This applies both to its direct use as a fuel and its role as a feedstock for emerging clean energy sources.

5.4. The role of research and technological development

This section was prepared with the collaboration of Daniella Fartes from the Center for Management and Strategic Studies (CGEE), who contributed the initial draft.

As outlined in the previous sections, the development of Brazil's sugar-energy sector has been shaped by numerous crises as well as periods of opportunity. In both cases, research, technological development and the adoption of innovations have been key drivers of progress, enhancing productivity, diversifying product offerings and reducing environmental impacts.

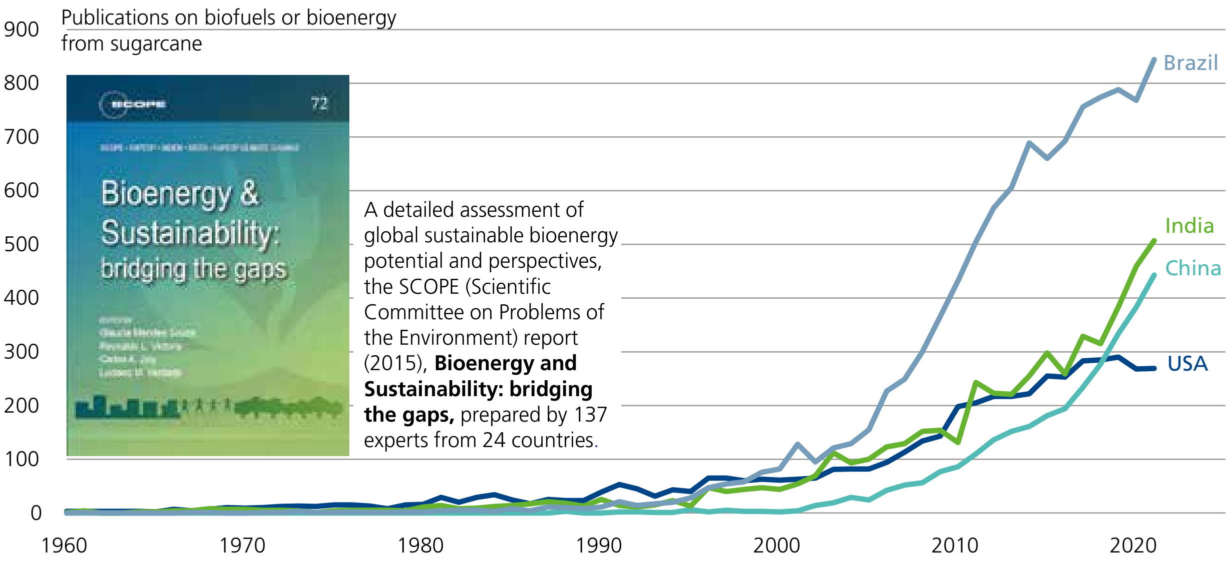
Sugarcane production and processing have long been central to Brazil's strategic discussions, with continuous State involvement and oversight facilitating the creation of a broad Technological Innovation System (TIS). A TIS can be defined as a coordinated network of institutions, companies, research organisations and individuals that promote and enable the development and implementation of technological innovations within a specific sector or context. This system encompasses not only research and development activities but also aspects related to education, public policy, funding, collaborative networks and an innovation-driven culture.

The TIS for bioethanol was gradually structured in response to various crises, aiming to maintain the sector's competitiveness and safeguard Brazil's energy security. Technological advancements have played a decisive role in market diversification and have often been central to business strategies, though with significant engagement from both federal and state governments. The federal government's primary role in this technological dynamic has been to secure markets, thereby enabling private companies to invest and ensure the dissemination of the necessary technologies for the development of the bioethanol sector (Lankriet & Poppe, 2018).

Some of the key historical milestones date back to 1873, during Brazil's imperial period, when the first direct State intervention sought to modernise the industry and strengthen its competitiveness in international markets (Dunham *et al.*, 2011). Other pivotal moments include the creation of the Proálcool programme in response to the oil crises of the 1970s, the introduction of flex-fuel vehicles and bioelectricity in the early 2000s and the current landscape featuring new products such as second-generation (2G) ethanol and biomethane. Across all these transformative phases, the explicit or implicit role of the TIS has been fundamental in driving innovation and productivity.

To this day, the TIS for sugarcane and bioethanol continues to support the importation, adaptation, dissemination and development of recent technologies, acting as a crucial engine of national progress. Through this system, Brazil has sought to master the technological trajectories of its sugar-energy industries and direct them towards addressing the various crises the sector has faced (Lankriet & Poppe, 2018).

GRAPH 31. Scientific publications on bioenergy using sugarcane, by country



A detailed assessment of global sustainable bioenergy potential and perspectives, the SCOPE (Scientific Committee on Problems of the Environment) report (2015), **Bioenergy and Sustainability: bridging the gaps,** prepared by 137 experts from 24 countries.

Source: Brito Cruz *et al.* (2022).

One indicator of the TIS's activity in bioethanol is the significant volume of scientific research on sugarcane-based bioenergy, as illustrated in Graph 31.

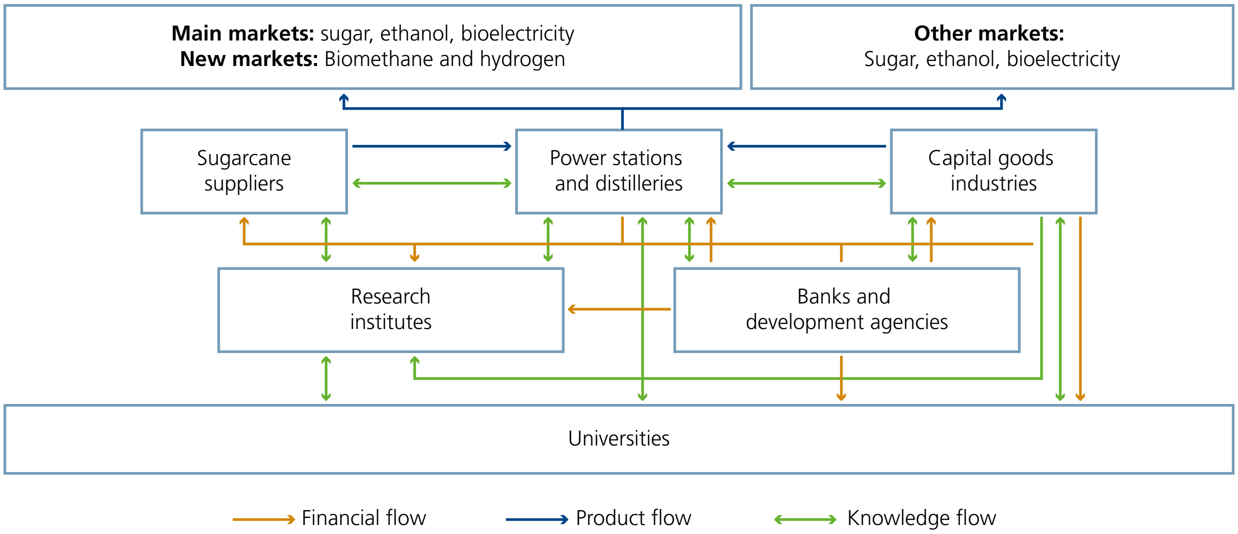
While Brazil remains a global leader in this field, other nations with strong biofuel potential, such as India and China, have been rapidly expanding their scientific knowledge in this area (Brito Cruz, 2022). The graph also features the cover of the report Bioenergy and Sustainability: Bridging the Gaps (Souza *et al.*, 2015), which was the result of two years of collaborative efforts by a diverse group of Brazilian and international experts evaluating the potential, impacts and benefits of sustainable bioenergy.

5.4.1. Elements of the bioethanol technological innovation system in Brazil

The main components of Brazil's technological innovation system (TIS) for bioethanol, along with the relationships between these elements—including material flows, financial resources and knowledge exchange—are illustrated in Figure 43 and are presented as follows:

At the core of the system are companies producing goods and services. In the case of the bioethanol TIS, these are generally well-established firms, many of which have diversified their product portfolios to maximise the utilisation of biomass. Key emerging products include second-generation (2G) ethanol, biomethane, a range of bioplastics and bioproducts and in the longer term, green hydrogen.

FIGURE 43. Structure and relationships within the bioethanol TIS in Brazil



Source: Adapted from Furtado *et al*. (2011).

While many bioethanol plants are vertically integrated, growing sugarcane on their own land or through leased farms, the majority also source raw materials from independent suppliers. In their study, Furtado *et al.* (2011) highlight the crucial role of agricultural research—an understandable focus given that nearly 80% of the final cost of bioethanol stems from sugarcane production. Both research institutions and universities have played and continue to play a significant role in improving productivity in the field, including the development of new, more productive and disease-resistant sugarcane varieties.

Over the past few decades, several important innovations have been introduced, such as mechanised harvesting, no-till planting, straw utilisation, fertigation with vinasse, and biogas production from vinasse and filter cake. However, factors such as lower profitability in certain periods and the expansion of sugarcane cultivation into regions with more challenging climates and soils, compared to traditional growing areas, have posed new and significant challenges for the bioethanol TIS (Nyko *et al.*, 2013).

Another key component of the bioethanol TIS is the capital goods industry, which provides equipment for agricultural operations, logistics, industrial processing and effluent management, as well as innovative inputs and services. These industries play a vital role in enabling the adoption of new processes and work methods. Their capacity to absorb and drive innovation has been crucial at various points in the ethanol sector's history—for example, during the transition away from pre-harvest sugarcane burning, which had been carried out manually in the fields. This shift was prompted by public concerns over the environmental and health impacts of sugarcane fires. In response, mechanised harvesting technologies were developed, allowing the use of biomass that would otherwise have been wasted. The mechanised process retains between ten and twenty tonnes of sugarcane residues (primarily straw) per hectare, compared to just three tonnes in manual harvesting (Vitti *et al.*, 2011). The primary application for this previously underutilised biomass has been in bioelectricity generation, as detailed later in this book.

Equally essential to the bioethanol TIS are banks and development agencies. These institutions play a critical role in supporting strategic initiatives related to the research, development, utilisation and commercialisation of bioethanol. They also provide targeted funding to modernise or implement innovative technologies within the bioenergy production chain.

The Brazilian Development Bank (BNDES)

A key financial institution within Brazil's Technological Innovation System (TIS) for bioethanol is BNDES, a federal public bank. In the 1980s, when several cogeneration projects were being developed at sugar-ethanol plants, BNDES played a crucial role by offering more attractive financing conditions for projects employing higher-pressure boilers, thereby improving efficiency. In 2007, BNDES established its Department of Biofuels, with five main objectives: (a) expanding production capacity; (b) encouraging innovation and technological development; (c) enhancing positive externalities; (d) promoting sustainability; and (e) contributing to the creation of a global bioethanol market (Milanez & Nyko, 2012).

Over the past two decades, BNDES has provided more than BRL 70 billion in funding for investments across the entire bioethanol production chain, focusing on optimising both industrial and agricultural capacity, including the renewal of sugarcane plantations. This has led to improvements in sugarcane production—such as higher-yielding varieties, more efficient land use and improved cultivation and harvesting practices—, as well as industrial advancements, including greater process efficiency, waste reduction and increased cogeneration.

Among BNDES initiatives to support research, the Industrial Technological Innovation Support Programme for the Sugar-Energy and Sugar-Chemical Sectors (PAISS)—a joint initiative with the Funding Authority for Studies and Projects (FINEP), a federal agency—allocated approximately BRL 2.5 billion between 2011 and 2014. This programme aimed to enhance productivity and drive the development of cellulosic ethanol, as well as new products and innovative processes in both industry and agriculture.

In 2021, BNDES launched the RenovaBio credit line, which allocated BRL 2 billion to biofuel producers, with the goal of incentivising emissions reductions through improved production and environmental practices. Companies that demonstrate compliance with the bank's carbon reduction targets—aligned with the RenovaBio programme—can benefit from reduced interest rates (BNDES, 2022).

5.4.2. Foundations of the bioethanol technological innovation system in Brazil

At the core of Brazil's bioethanol technological innovation system (TIS) lie research institutes, technology companies and universities—fundamental pillars driving technological progress in the sugarcane and bioethanol sector. These institutions play a crucial role, particularly in the agricultural stage of production but also in industrial processes, as well as in socioeconomic and environmental studies.

Amongst the pioneering institutions in this field are the Agronomic Institute (IAC) and the Interuniversity Network for the Development of the Sugar Energy Sector (RIDESA), both of which have for decades been dedicated to breeding and selecting higher-yielding more resistant sugarcane varieties. Today, numerous other institutions and research groups continue to study, experiment and analyse bioethanol production and usage, generating and disseminating both fundamental and applied knowledge.

Agronomic Institute (IAC)

The IAC was founded in 1887 and operates under the administration of the São Paulo State government. As early as 1892, the IAC conducted its first study on 42 sugarcane varieties under two different cultivation conditions. In 1934, it launched a pioneering sugarcane breeding programme, leading to the development of the first IAC sugarcane varieties in the following decades. Since then, the institute has carried out extensive research on fertilisation, liming, planting schedules, spacing and vinasse application (IAC, 2024).

As sugarcane agribusiness expanded across Brazil's Central-Southern region, the expertise developed at IAC helped establish other breeding programmes. One such initiative, created in the 1970s by the Copersucar Technology Centre, enabled the joint use of the Camamu Experimental Crossbreeding Station in Bahia with IAC. In 2009, IAC's Sugarcane Programme acquired land in Uruçuca, Bahia, through the Agronomic Research Support Foundation, where it established the IAC Sugarcane Hybridisation Station. This station houses the world collection of sugarcane varieties, organised by the International Society of Sugar Cane Technologists (ISSCT), forming one of the largest living repositories of sugarcane genetic material worldwide.

From the 1990s onwards, IAC strengthened its engagement with the sugar-energy sector. In 1992, it established the Sugarcane Agronomic Group in Ribeirão Preto, São Paulo, bringing together professionals from mills and cooperatives, researchers and experts from industries involved in inputs, machinery and other production factors. This group plays a key role in identifying research demands within the sector.

In 1994, the IAC Sugarcane Programme was introduced as a collaborative initiative between industry players, the Agronomic Institute, and the Foundation for Agricultural Research Support, significantly expanding IAC's experimental network in sugarcane research. Today, this programme is managed by the IAC Sugarcane Centre in Ribeirão Preto, working alongside other IAC units in fields such as genetic improvement, soil science, environmental characterisation, crop management, pest and disease control and yield forecasting. IAC operates a network of experimental sites across 11 Brazilian states in partnership with around 160 companies (IAC, 2023b).

The technological package developed by the IAC Sugarcane Programme includes 34 sugarcane varieties, which have contributed to an increase in productivity from 70 to around 87 tonnes per hectare, over an average of five harvest cycles, with some units achieving over 100 tonnes per hectare. The programme has also led to a 30% productivity increase through the Environmental Matrix, a 90% accuracy rate in crop forecasting using PrevClimaCana IAC and the introduction of the Pre-Sprouted Seedling System (MPB), which has significantly outperformed conventional mechanised sugarcane planting methods (IAC, 2023c).

Interuniversity Network for the Development of the Sugar Energy Sector (RIDESA)

In 1971, the Sugar and Alcohol Institute (IAA), previously discussed in this chapter, established the National Sugarcane Breeding Programme (Planalsucar) to improve yields in both agricultural and industrial stages of production. This nationwide programme was instrumental in ensuring that the Proálcool targets were met, particularly through genetic improvement of sugarcane varieties, leading to the development of RB cultivars. From its inception, Planalsucar relied on the Sugarcane Germplasm Bank at the Serra do Ouro Flowering and Crossbreeding Station in Murici, Alagoas, which had been established in 1967 by the Alagoas Sugarcane Experimental Station under the IAA.

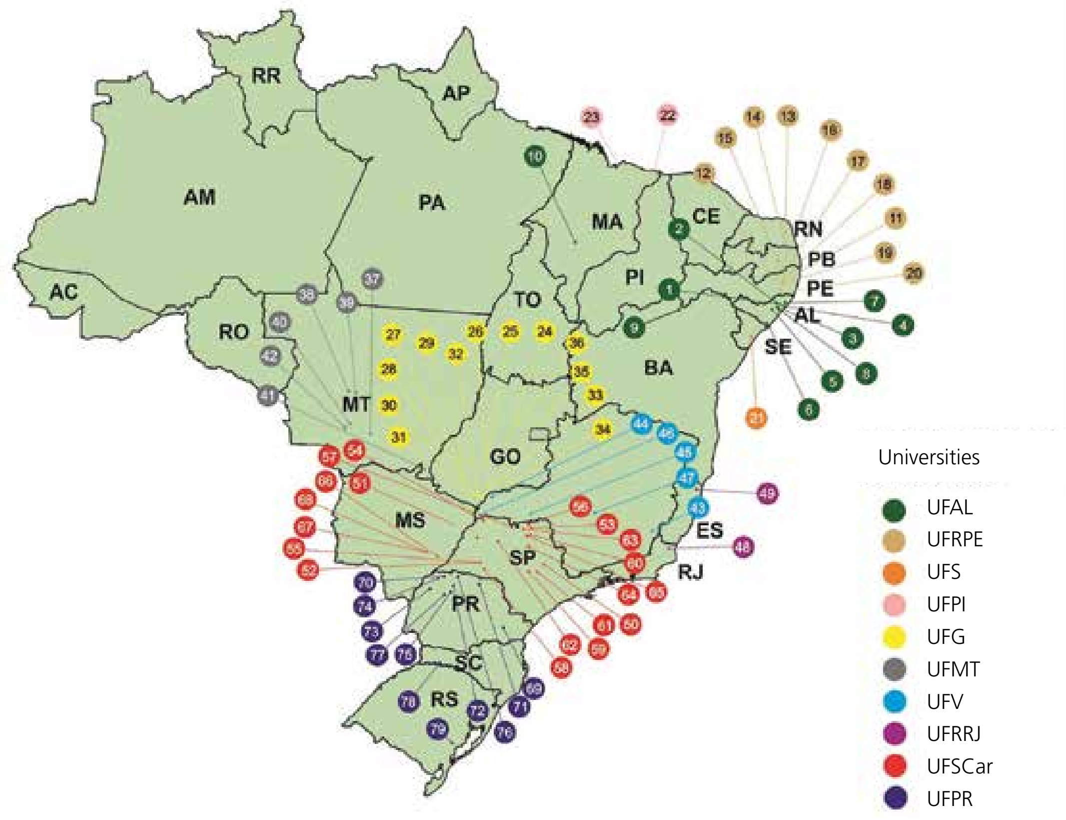
In addition to genetic improvement, Planalsucar played a key role in modernising agricultural and industrial mechanisation, introducing biological pest control, promoting the use of liming and fertilisation, optimising industrial processes for sugar and ethanol production and establishing payment standards based on sucrose content (RIDESA, 2024).

Following the dissolution of the IAA in 1990, Planalsucar was disbanded, and its human, physical and technological resources were transferred to federal universities. The Brazilian Presidency's Secretariat for Regional Development established a new institutional model for sugarcane research, placing responsibility for breeding programmes within a network of federal universities. This led to the creation of RIDESA, composed of the Federal Universities of Alagoas (UFAL), Rural of Pernambuco (UFRPE), Viçosa (UFV), São Carlos (UFSCar), Rural of Rio de Janeiro (UFRRJ), Paraná (UFPR) and Sergipe (UFS). In later years, the Federal Universities of Goiás (UFG), Mato Grosso (UFMT) and Piauí (UFPI) also joined the programme (RIDESA, 2024).

Despite initial challenges, these universities successfully formed a partnership agreement that respects the diversity of contexts and resources within the network. The programme is primarily funded by private investment, with each university running its own Sugarcane Breeding Programme (PMGCA) whilst jointly maintaining a Germplasm Bank and Crossbreeding Experiment Stations. The costs are distributed proportionally amongst universities based on revenue from partnerships with sugarcane producers.

The universities share knowledge and research findings, particularly regarding the most promising sugarcane clones, which are then jointly evaluated. RIDESA currently operates 101 research units (RIDESA, 2024), including university laboratories, crossbreeding stations, experimental stations and selection sites. Many of these selection sites are managed in partnership with private sugarcane industry players (RIDESA, 2021).

FIGURE 44. Universities and research facilities of RIDESA's Sugarcane Breeding Programme in 2021



Source: RIDESA (2021).

In 2020, RIDESA universities marked 50 years of RB sugarcane varieties and 30 years since the network's establishment, celebrating the 114 RB varieties developed since 1971, the year Planalsucar was created. Of these, 60 varieties were developed and released by RIDESA, with crossbreeding carried out after 1990 by the universities themselves (RIDESA, 2021). Each variety is tailored to specific characteristics, such as productivity, sugar content, maturation period, disease resistance, drought tolerance, suitability for mechanised harvesting and overall stability.

Developing a new sugarcane variety requires around ten years of experimentation, with RIDESA estimating the cost at USD 10 million per variety. This is considered relatively low due to the collaborative efforts between universities and industry partners, who provide land, inputs, labour and laboratory analyses for selection, experimentation and clone multiplication (RIDESA, 2021). For the 2023/2024 harvest, RB varieties accounted for over 65% of Brazil's sugarcane cultivation area (RIDESA, 2024).

Brazilian Agricultural Research Corporation (EMBRAPA)

EMBRAPA is a state-owned company linked to the Ministry of Agriculture and Livestock. Established in 1973, its mission is to develop the technological foundations for a uniquely tropical model of agriculture and livestock farming in Brazil. With seven central units and 43 decentralised units (including ecoregional, product-focused and basic research units) spread across the country and more than 8,000 employees, EMBRAPA has played a pivotal role in the expansion and diversification of Brazilian agribusiness over recent decades. The sector not only meets domestic demand, but also generates significant export surpluses. Brazil currently exports over 350 different agribusiness products and is the world's leading exporter of soybeans, coffee, sugar, orange juice, bioethanol, beef and poultry (EMBRAPA, 2022a).

Despite its expertise in agricultural research, during the existence of Planalsucar under the IAA, EMBRAPA's role in the sugarcane sector was complementary. However, since 1990, some of its research units have increasingly focused on specific areas within the sugar-energy industry, making valuable contributions, as outlined below.

EMBRAPA Meio Ambiente, in Jaguariúna, São Paulo, specialises in the relationship between agriculture, livestock, forestry, agribusiness and the environment. It aims to balance the demands of agricultural production systems with the need to conserve natural resources and protect the environment. Its main research areas include sustainability, climate change and biodiversity. The unit played an active role in designing and implementing RenovaBio and continues to monitor its progress (EMBRAPA, 2024a).

EMBRAPA Solos, in Rio de Janeiro, works to assess and implement preventive measures to mitigate environmental risks caused by the improper use of soil and water resources. In collaboration with other EMBRAPA units, such as EMBRAPA Territorial in Campinas, São Paulo (EMBRAPA, 2024b), and using digital processing techniques and geographic information systems, this centre produced Agroecological Zoning Studies for rain-fed sugarcane cultivation in 2009 and oil palm in 2010. These studies classify the land by cross-referencing climatic suitability (precipitation, temperature, frost risk and dry spells) with soil characteristics while also considering restrictions related to topography, land use priorities and other factors. These zoning studies are essential for a robust assessment of Brazil's bioenergy potential (EMBRAPA, 2024c).

EMBRAPA leads a national agricultural research network that brings together different institutions. In addition to its decentralised units, the network includes 17 state agricultural research organisations, universities and federal or state research institutes, as well as private companies and foundations (EMBRAPA, 2022b).

Brazilian Biorenewables National Laboratory (LNBR)

The research center is part of the Brazilian Center for Research in Energy and Materials (CNPEM) in Campinas, São Paulo, which is linked to the Ministry of Science, Technology and Innovation (MCTI). With specialized laboratories and an experienced team of about thirty researchers, it focuses on science and technology for a low-carbon bioeconomy, conducting advanced research on biomass, biotechnology and biorefineries, including genetic studies, enzyme development, process modeling and sustainability assessment (LNBR, 2025).

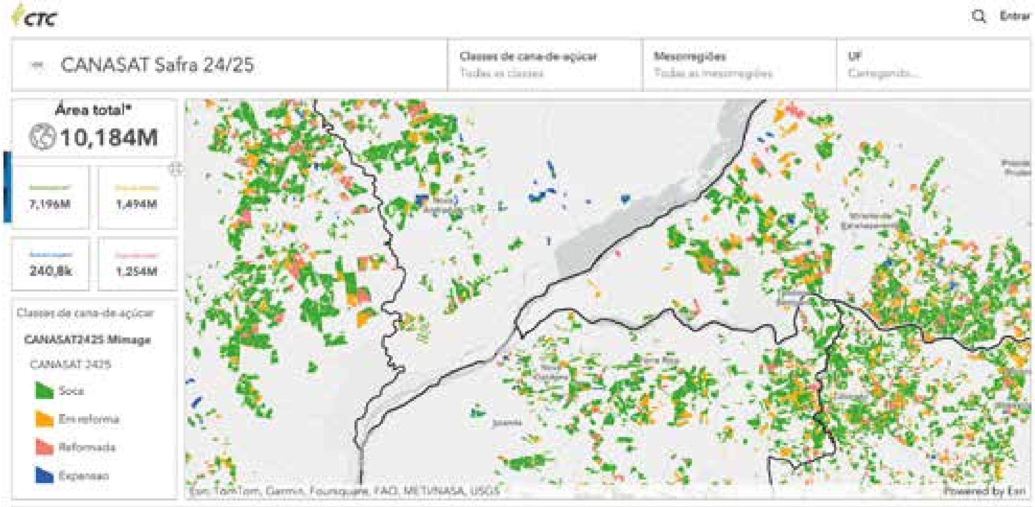
LNBR's Virtual Sugarcane Biorefinery supports the evaluation of the economic and environmental performance of biofuels, bioelectricity and biochemicals, informing public policy, industrial innovation and the transition to renewable, sustainable energy systems. LNBR also developed the SUCRE project, dedicated to the enhanced use of sugarcane straw, presented in Chapter 6.

National Institute for Space Research (INPE)

Headquartered in São José dos Campos, São Paulo, with laboratories in various Brazilian cities, the National Institute for Space Research (INPE) was established in 1961 and operates under the Ministry of Science, Technology and Innovation. INPE conducts a wide range of studies and activities related to environmental monitoring, meteorology and climate studies, satellite development, remote sensing technology and space sciences (INPE, 2024).

In 2003, INPE launched the CanaSat Project, which maps sugarcane plantations using satellite imagery. Since then, it has regularly provided detailed images at the municipal level, offering consistent data on sugarcane-growing areas and their production cycle status. It identifies fields undergoing renewal in the process of being reformed, in ratoon growth or under expansion, as shown in Figure 45. CanaSat also tracks areas where sugarcane straw has been burned. This information is easily accessible online and widely used by government agencies, the agro-industrial sector and environmental bodies involved in sugarcane production.

FIGURE 45. Example of a CanaSat image showing sugarcane fields and their production cycle stage in the Pontal do Paranapanema region* for the 2024/2025 harvest



*Region in the far west of the state of São Paulo and in the neighbouring areas of the states of Paraná and Mato Grosso do Sul.

Source: CTC (2025).

Sugarcane Technology Centre (CTC)

In the private sector, the Sugarcane Technology Centre (CTC) stands out as a key research institution. It was founded in 1969 as the Copersucar Technology Centre to provide innovative technological support to this cooperative of sugar and bioethanol producers. In 2005, it became independent from Copersucar, forming a non-profit private association, and, in 2011, it was transformed into a joint-stock company with major sugar-energy sector groups as shareholders. In 2014, BNDES joined CTC's shareholder structure.

Based in Piracicaba, São Paulo, and operating across Brazil, CTC has been running a sugarcane breeding programme since the 1970s. It released its first CTC variety in 1983 and currently offers 28 varieties. Covering all stages of the sugarcane agro-industrial production chain, CTC has contributed to the automation of industrial processes, supported the adoption of mechanised harvesting, optimised harvesting and transportation systems and introduced technologies for collecting and processing sugarcane straw (CTC, 2024).

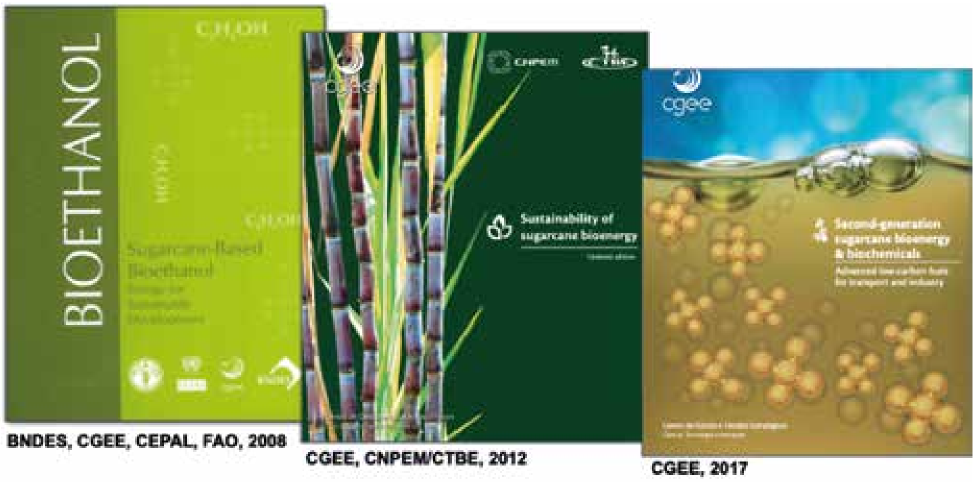
In 2018, CTC established its subsidiary, CTC Genomics, in St. Louis, Missouri, USA, to advance research in genome editing and the development of synthetic seeds. The CTC website also provides access to CANASAT, as described earlier.

Center for Management and Strategic Studies (CGEE)

Established in 2001, the Center for Management and Strategic Studies (CGEE) is a social organisation linked to the Ministry of Science, Technology and Innovation (MCTI). It conducts prospective studies and research in science and technology, evaluating strategies and assessing the economic and social impacts of policies, programmes and scientific and technological projects using indicators and analyses. CGEE has been active in specific sectors and themes, including climate change, strategic materials, nanotechnology, bioeconomy and bioenergy (CGEE, 2024).

To promote the sustainable production and use of bioethanol, support the adoption of innovations in this agroindustry and facilitate the integration of bioethanol into the portfolio of technologies for energy transition, CGEE has contributed to policy formulation, conducted studies, participated in technical and scientific events and published influential works. In 2008, in a joint publication with BNDES, the Economic Commission for Latin America (CEPAL) and the Food and Agriculture Organization of the United Nations (FAO), it released *Sugarcane-Based Bioethanol: Energy for Sustainable Development in four languages*. In 2012, in collaboration with the Brazilian Bioethanol Science and Technology Laboratory (CTBE) of the Brazilian Center for Research in Energy and Materials (CNPEM), it published *Sustainability of Sugarcane Bioenergy*, and, in 2017, CGEE published *Second Generation Sugarcane Bioenergy & Biochemicals*.

FIGURE 46. CGEE publications on bioenergy and sugarcane-derived bioproducts



BNDES, CGEE, CEPAL, FAO, 2008

CGEE, CNPEM/CTBE, 2012

CGEE, 2017

Source: CGEE.

Universities

Universities play a fundamental role in the Technological Innovation System (TIS) for bioethanol by training professionals across the diverse disciplines and topics related to the production and use of bioethanol. Beyond their essential role in professional education, universities also contribute through relevant studies and research, particularly at the postgraduate level, often exploring emerging and early-stage themes.

Professionals working in the bioenergy agroindustry require training not only in the technological aspects of production within the fields of engineering, agronomy and the physical, natural and biological sciences. There is also a demand for specialists capable of evaluating and analysing the broad social, economic and environmental implications, as well as political and legal aspects, which involve fields such as social sciences, economics and management.

Several Brazilian universities have been actively engaged in the TIS for bioethanol, both contributing to and benefiting from it. Located in the country's main sugarcane-producing and processing region, the three São Paulo State universities have played a particularly vital role. The University of São Paulo (USP), especially through the Luiz de Queiroz College of Agriculture (ESALQ), has a long-standing tradition in sugarcane technology. Additionally, various departments of the University of Campinas (UNICAMP) and São Paulo State University (UNESP) offer courses and research groups focused on sugarcane bioenergy, producing a significant volume of academic work in this field. Since 2014, these universities have collaborated on an Integrated PhD Programme in Bioenergy, further strengthening their expertise.

BIOEN, the Bioenergy Research Programme established in 2008 by the São Paulo Research Foundation (FAPESP), primarily operates in partnership with university and research institutions in São Paulo State. It aims to stimulate and coordinate research and development activities related to sustainable bioenergy production in Brazil and internationally. The programme supports activities in five key areas: biomass production, conversion technologies, end-use applications, biorefineries and sustainability.

Amongst the federal universities, beyond those involved in RIDESA, other institutions have also contributed by conducting studies and experiments in sugarcane bioenergy and bioethanol, including the Federal Universities of Itajubá (UNIFEI), Lavras (UFLA), Minas Gerais (UFMG) and Rio de Janeiro

(UFRJ). Specifically in the field of bioethanol as a vehicle fuel, the Mauá Institute of Technology (IMT) and the Aeronautics Institute of Technology (ITA) stand out. Given the significant role of bioenergy in Brazil, nearly all Brazilian universities show interest and engage in some form of activity in this area.

Other institutions generating and disseminating knowledge and technology in bioethanol

Over the past two decades, the expansion of bioethanol production and its economic significance in Brazil have been remarkable. This growth has coincided with the evolution of the legal and regulatory framework, which has reduced government intervention and encouraged competitiveness and efficiency. At the same time, new perspectives and standards have emerged in this agroindustry, with increasing emphasis on environmental aspects and the consolidation of digital information systems. In this context, several new institutions have become key players in Brazil's bioethanol innovation system, disseminating, evaluating and promoting the adoption of innovations in the sector.

Today, consultancy firms based in Brazil, as well as university-affiliated institutes, provide detailed data on the bioethanol market and other products within the sugar-energy industry. These include pricing, input costs, domestic and export market volumes and stock levels, some of which are regionalised and comparable with international data. Frequent studies and analyses are also published, offering insights into economic and legal trends that help market players make strategic decisions. In some cases, these consultancies have been established around experienced private consultants with strong sector connections and credibility. Some of the most notable institutions, which specialise in providing reliable and contextualised information, are briefly introduced below:

Datagro, with over 35 years of experience, Datagro monitors markets for sugar, ethanol, energy, maize, soy, meat and their broader economic interactions. It also organises industry meetings and develops market analyses and projections (Datagro, 2024).

Canaplan, established in 1983, Canaplan supports the competitiveness of the sugar-energy sector, focusing on costs, technology and operations, planning and public policy (Canaplan, 2024).

CEPEA, created in 1982 and linked to the Department of Economics, Management and Sociology at ESALQ/USP, CEPEA conducts research on production chain dynamics and the integrated functioning of agribusiness. It regularly estimates the agribusiness gross domestic product (GDP) and workforce demand in the sector (CEPEA, 2024).

Agroicone, founded in 2013, Agroicone advises businesses, governments and international agencies, particularly on environmental issues such as climate change and biodiversity in agricultural and bioenergy production. It conducts lifecycle assessments, analyses land use and public policies and supports environmental certification (Agroicone, 2024).

Pecege Consultoria e Estudos, operating since 2007, Pecege specialises in collecting primary data, conducting economic and comparative analyses, making projections and developing tools to enhance understanding of the sugar-energy sector. It employs various digital platforms and engages directly with industry players (Pecege, 2024).

Additionally, innovative technology companies operating in areas related to the sugar-energy production system are important components of Brazil's bioethanol innovation system. Many of these companies have emerged as start-ups from academic projects, offering services in climate studies, industrial automation, satellite image processing, drone technology and precision agriculture.

Companies in the communications sector and organisers of exhibitions and trade fairs also contribute to the innovation system by promoting bioenergy production technologies and connecting suppliers with buyers. Over the past few decades, the number of magazines and newsletters covering the bioethanol agroindustry has grown significantly, with regular print editions and online publications. Industry events have also gained prominence, attracting a wide range of stakeholders.

The relationships between players in the bioethanol innovation system are shaped by national programmes, policies and regulations that influence the entire industry. The significance of Proálcool in the sector's development is undeniable. Today, policies such as mandatory blending mandates, Renovabio and the Future Fuel Law demonstrate how Brazil continues to strategically guide the sustainable development of its bioenergy sector.

5.5. Sugarcane genomics and the future of bioethanol

This section is inspired by the document Sugarcane Genome and Biotechnology, *prepared by Carolina Gimiliani Lembke and Glaucia Mendes Souza from the Department of Biochemistry at the Institute of Chemistry, University of São Paulo (USP), and adapted by the editors and authors to align with the scope of this book.*

The adoption of selected varieties in sugarcane breeding programmes has led to significant gains in productivity in Brazil. In the 1970/1971 harvest, when sugarcane fields covered 1.7 million hectares, productivity was 46.2 tonnes per hectare and agro-industrial yield stood at 4.2 tonnes of sugar per hectare. After 50 years, these indicators have improved considerably. In the 2019/2020 season, 8.4 million hectares were harvested—nearly five times more—, yielding 76.5 tonnes per hectare (+65%) and an agro-industrial yield of 10.7 tonnes of total recoverable sugars (TRS) per hectare (+155%) (RIDESA, 2021). These are remarkable increases in both the quantity and quality of sugarcane production.

Several factors have contributed to this progress, including advancements in cultivation techniques, fertilisation and liming, fertigation with vinasse and ratoon crop protection. However, the primary driver has undoubtedly been the genetic improvement of sugarcane varieties, which have been scientifically hybridised and selected. In other major crops, variety improvement, alongside increased fertiliser use, has also been a key factor in boosting production. Globally, cereal productivity averaged 1.4 tonnes per hectare in 1961, rising to 4.2 tonnes per hectare by 2021—a threefold increase (WB, 2024).

The search for new sugarcane varieties

Thanks to its rapid growth and high productivity, compared with other grasses and woody plants, sugarcane is one of the most efficient crops for energy production. It can generate bioethanol from its sugars and utilise its solid lignocellulosic components, which have a low lipid content—a benefit for certain industrial processes.

As a C4 photosynthetic plant, sugarcane is highly efficient at converting solar energy into biomass. One of its key advantages is its ability to regenerate after harvesting, preserving its root system and allowing multiple harvests—typically four to five—without the need for replanting. This lowers production costs compared with most other biomass sources, which require annual replanting (Botha, 2009).

The development of today's sugarcane has been a long journey, and further improvements will require overcoming new challenges. The modern sugarcane plant does not exist in nature; it is a human creation. The most likely origin of its ancestral species is Papua New Guinea, where it was cultivated around 10,000 years ago. Appreciated for its sweet taste, sugarcane spread along migration routes through Persia and the Mediterranean, reaching Europe. During the Age of Exploration, it was introduced to Brazil soon after the Portuguese colonisation and later reached the Dominican Republic via Spanish settlers before spreading throughout the Caribbean.

As sugarcane cultivation expanded across different regions, new challenges arose, including pests and diseases. Around two centuries ago in India, hybrids of *Saccharum officinarum* and *Saccharum spontaneum* were developed, producing plants with greater disease resistance. The success of these hybrids led to the establishment of breeding programmes in various countries, where new varieties were selected for adaptation to local conditions, higher sugar content and greater productivity. However, until the advent of molecular genetics, it was not widely understood that successive hybridisation processes were creating extraordinarily complex genomes, with multiple gene copies and significant genetic variation between varieties.

Indeed, modern sugarcane possesses one of the most complex genomes in the plant kingdom. Its genome is approximately 10 gigabases (Gb) in size, whereas sorghum and rice have much smaller genomes of around 730 megabases (Mb) and 380 Mb, respectively (D'Hont & Glaszmann, 2001).

The new challenges of sugarcane genetic improvement

Compared with other major crops, sugarcane has been cultivated on smaller areas and primarily in tropical countries, where funding for agronomic research is more limited. As a result, there is still significant potential to increase its productivity. Crucially, given sugarcane's role in bioenergy production, these productivity gains must not depend on excessive fertiliser use. The production of nitrogen-based fertilisers, in particular, is highly energy-intensive and contributes significantly to greenhouse gas emissions. The challenge is to produce bioenergy efficiently, achieving high yields per hectare with minimal energy inputs.

Sugarcane breeding is an ongoing process that must continue. Waclawovsky *et al.* (2010) estimate a theoretical maximum yield of around 381 tonnes per hectare—well above the highest productivity levels currently achieved. Besides yield, other desirable traits must also be enhanced, such as resistance to emerging pests and diseases and suitability for mechanised harvesting. The question is how to advance sugarcane breeding by leveraging modern genetic technologies. Can the latest genomic tools make breeding more efficient and precise?

A leading sugarcane biologist, Paul Moore, has advocated for

> *[…] high-throughput genomic approaches to generate large datasets that can be analysed using appropriate models in a systems-based approach. This would enable the development of varieties with improved physiological traits, such as enhanced photosynthetic efficiency, carbon partitioning between sucrose and fibre, water-use efficiency, nitrogen-use efficiency and resistance to pests and pathogens.* (Moore, 2009)

This represents a shift from conventional hybrid breeding—guided by accumulated experience but still slow and uncertain—towards a genome-based approach. The use of molecular tools would make the process more objective and accelerate genetic gains.

To achieve progress in sugarcane breeding, it is essential to recognise the complexity of this crop. The growing demand for sophisticated traits, such as high biomass productivity and drought tolerance, necessitates a deeper understanding of the genetic contributions from varied species. This includes identifying chromosomal contributions, gene copy number variations and inter-chromosomal translocations (Piperidis & D'Hont, 2020).

A significant step forward was taken in recent years with advances in genome sequencing technologies, leading to the pioneering sequencing of the gene-rich regions of a modern sugarcane cultivar (Souza, N.R.D. *et al.*, 2019)—a project led by Brazilian researchers. Today, traditional breeding can be assisted by molecular markers, accelerating the association of desirable traits with genetic tools.

Another approach to sugarcane improvement is genetic modification. The first genetic transformations in sugarcane took place in the 1990s (Bower *et al*., 1996; Budeguer *et al*., 2021), initially to refine transformation protocols and advance scientific research. However, the commercial use of transgenic sugarcane remains limited to insect-resistant varieties, such as those developed by CTC and approved for commercial release in Brazil. These plants incorporate the *bet*A gene from *E. coli* and *Rhizobium meliloti*, which encodes choline dehydrogenase—an enzyme that catalyses the formation of glycine betaine, an osmoprotectant. To date, at least 11 genetically modified sugarcane events have been approved for cultivation, including plants with enhanced resistance to *Lepidoptera* and *Coleoptera* insects, tolerance to glyphosate herbicide and drought resistance (ISAAA, 2024).

Ultimately, the challenge lies in identifying key genes, addressing genotype-specific complexities and uncovering the missing links that will enhance biomass accumulation and quality. This is particularly demanding in sugarcane, given its highly complex genome. To overcome these challenges, genomic databases must be developed and fully exploited, allowing functional genomics to drive sugarcane improvement. This will open new opportunities for molecular breeding, enabling significant and broad-spectrum enhancements across different production systems and uses.

5.5.1. Drought memory in sugarcane and its impact on biomass and bioenergy production

> *At the invitation of the editors, Rafael Vasconcelos Ribeiro from the Laboratory of Cultivated Plant Physiology at the Institute of Biology, University of Campinas (UNICAMP), prepared this section, presenting a topic at the forefront of plant science.*

Advancements in agricultural management, combined with improved plant nutrition and the crucial role of genetic improvement, have been the foundation of a thriving agricultural sector, positioning Brazil as one of the leading bioeconomies, particularly in bioenergy production and its energy matrix. Disruptive technologies based on genetic engineering have been proposed to enhance agricultural productivity, yet their real impact on increasing biomass and bioenergy supply still requires validation through field experimentation.

Over the past decade, a new research field has captured the attention of the scientific community: stress memory in plants. Although still in its early stages, the study of plant memory and its application in agriculture could revolutionise conventional farming practices (Pissolato *et al.*, 2024). This brief text offers readers a fresh perspective by presenting recent advances in a crop of great significance to Brazil—sugarcane—and its performance under water deficit conditions.

In simple terms, memory can be defined as the ability to retrieve and access previously learned information through associative mechanisms, the storage of knowledge acquired from an organism's activity or experience, or the capacity to retain information (Galviz *et al.*, 2020). While it is easy to acknowledge that a USB drive has a memory, the idea that plants possess this capability is often met with scepticism. However, plants are living organisms capable of responding to environmental challenges and "learning" from past experiences, thereby demonstrating memory.

For the term to be appropriately applied, a plant's subsequent responses must be clearly based on stored information from past events, necessitating an experimental design that is far from trivial. Another key point is that memory can also negatively affect a plant's functional organisation. Amongst the molecular mechanisms associated with memory, researchers have proposed the accumulation of post-translational modifications in one or more signalling proteins, transcriptional responses involving changes in gene expression (either activation or repression) mediated by transcription factors, the action of phytohormones and epigenetic modifications such as chromatin remodelling, DNA methylation and histone modification (Galviz *et al.*, 2020).

There is potential to stimulate drought memory in sugarcane, given that water scarcity is the primary environmental factor limiting its development in Brazil. With a well-designed experimental approach, it was established that two cycles of dehydration and rehydration were sufficient to induce drought memory in sugarcane. This memory resulted in increased photosynthesis and improved water-use efficiency, ultimately leading to greater root system development and increased above-ground biomass (Marcos *et al*., 2018a).

Further studies revealed that this memory could be passed on to the next generation through vegetative propagation—an example of intergenerational memory (Galviz *et al*., 2020; Pissolato *et al*., 2024). As a result, propagules obtained from previously stressed plants exhibited enhanced root system growth and better recovery of photosynthetic capacity after rewatering (Marcos *et al*., 2018b).

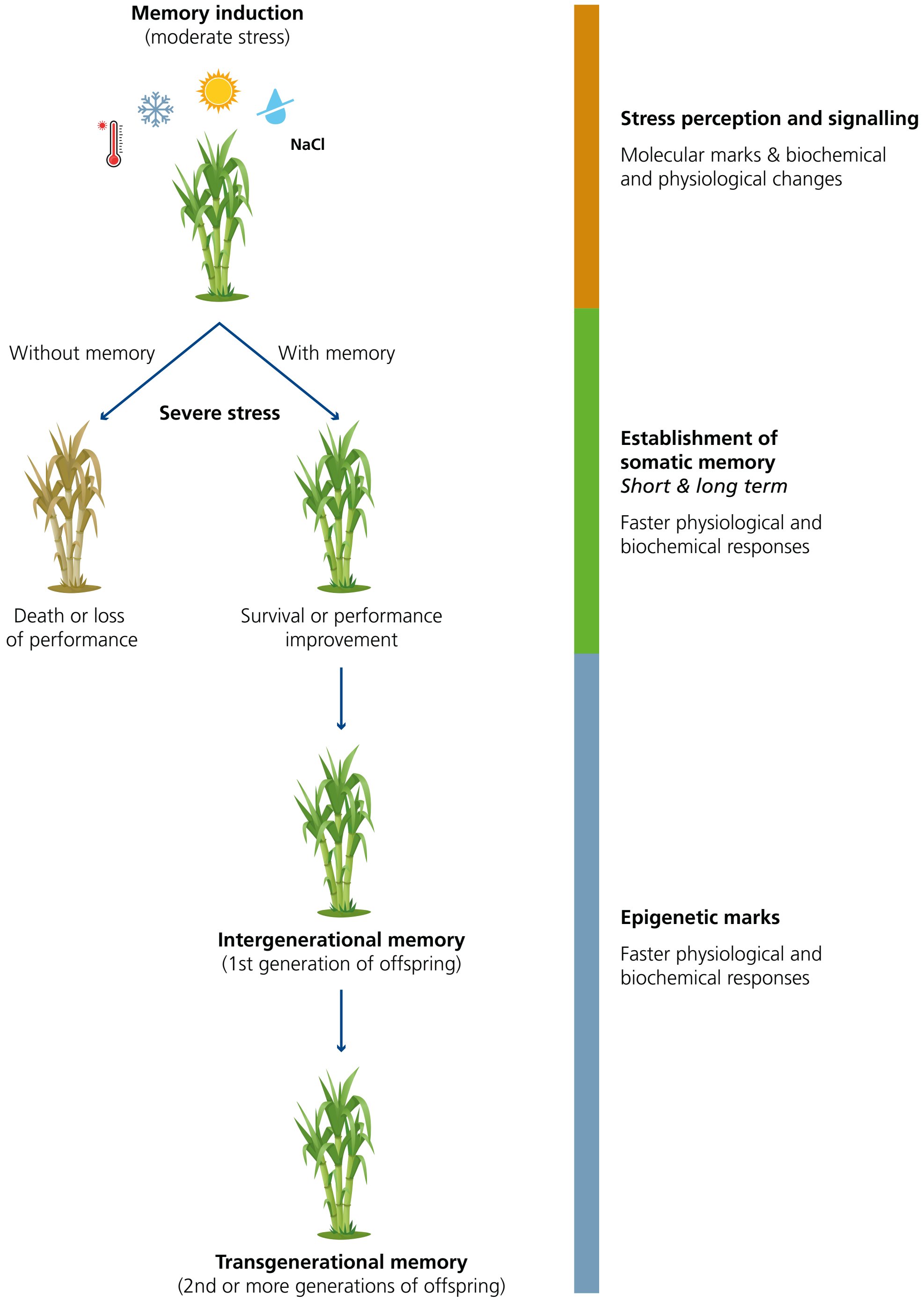
These proof-of-concept findings, obtained under controlled conditions, needed to be confirmed in field trials to determine whether drought memory in sugarcane could have practical benefits for agricultural productivity. Propagules from stressed plants were therefore planted under field conditions and monitored over the long term. The primary benefits observed in these small-scale field trials included significant increases in above-ground biomass production, root system growth and sugarcane's technological quality (sugar yield) (Pissolato, 2024).

Figure 47 outlines the main stages of the sugarcane memory induction process. An environmental stress event can induce memory in plants with this capacity, which in turn is based on molecular markers and physiological and biochemical changes. Once memory is established, plants either survive or exhibit enhanced performance when faced with subsequent stress events of similar or even greater intensity. Epigenetic markers improve the performance of future generations under stressful conditions.

It appears that memory induction varies depending on the plant's phenological stage and sugarcane cultivar, which is expected from a biological perspective. In practical terms, pre-germinated plants with greater drought tolerance could be produced using less water (due to irrigation suspension periods) and less energy (by reducing the need for irrigation system operation). Additionally, more drought-tolerant propagules could be obtained from plants grown in water-deficient regions, such as the Brazilian Cerrado.

Currently, the key technical and scientific challenges are to expand field studies—covering larger areas and more cultivars—and to establish the molecular basis of drought memory in sugarcane. While ongoing research may reveal how drought memory affects plant metabolism and gene expression patterns, the most striking aspect is that managing sugarcane memory could increase agricultural productivity and biomass and bioenergy supply for a society committed to sustainability and the well-being of future generations.

FIGURE 47. General model of memory establishment in plants



Source: Adapted from Pissolato *et al*. (2024).

6.

Integrating processes, circularity and diversity in bioenergy production: the Brazilian model

Biorefining is the sustainable processing of biomass into a spectrum of bio-based products (food, feed, chemicals, materials) and bioenergy (biofuels, power and/or heat).

International Energy Agency (IEA),
Bioenergy Task 42, 2019.

Building on the themes from Chapter 4: *Advanced technologies in bioenergy and biomaterials production* and considering real-world examples widely adopted in Brazil, this chapter presents four case studies demonstrating the efficient and comprehensive use of processed biomass. These systems utilise what would otherwise be waste and residues from the industrial process to create valuable co-products, such as electricity, biogas, sugarcane straw, and by-products from maize ethanol production.

These technologies help diversify production, improve process efficiency and add value to waste streams, promoting greater integration and circularity in production processes, with positive effects on both the environment and the economic sustainability of the agroindustry.

6.1. Bioelectricity in the sugarcane industry

In sugarcane, roughly one-third of the solar energy absorbed is stored as sugar, while the remaining two-thirds are found in the plant's fibre, composed of cellulose, hemicellulose and lignin. These make up the bagasse and sugarcane straw (the top of the stalk and leaves). Bagasse, a by-product of extracting juice from sugarcane stalks, has traditionally been used as fuel in sugar mills worldwide. Similarly, the use of sugarcane straw as fuel—a by-product of the sugarcane harvest—has become increasingly common, particularly in Brazilian mills over the past few decades, as explained later in this chapter. In both cases, these solid biofuels are mainly used to generate the distinct types of energy required by sugar and ethanol mills.

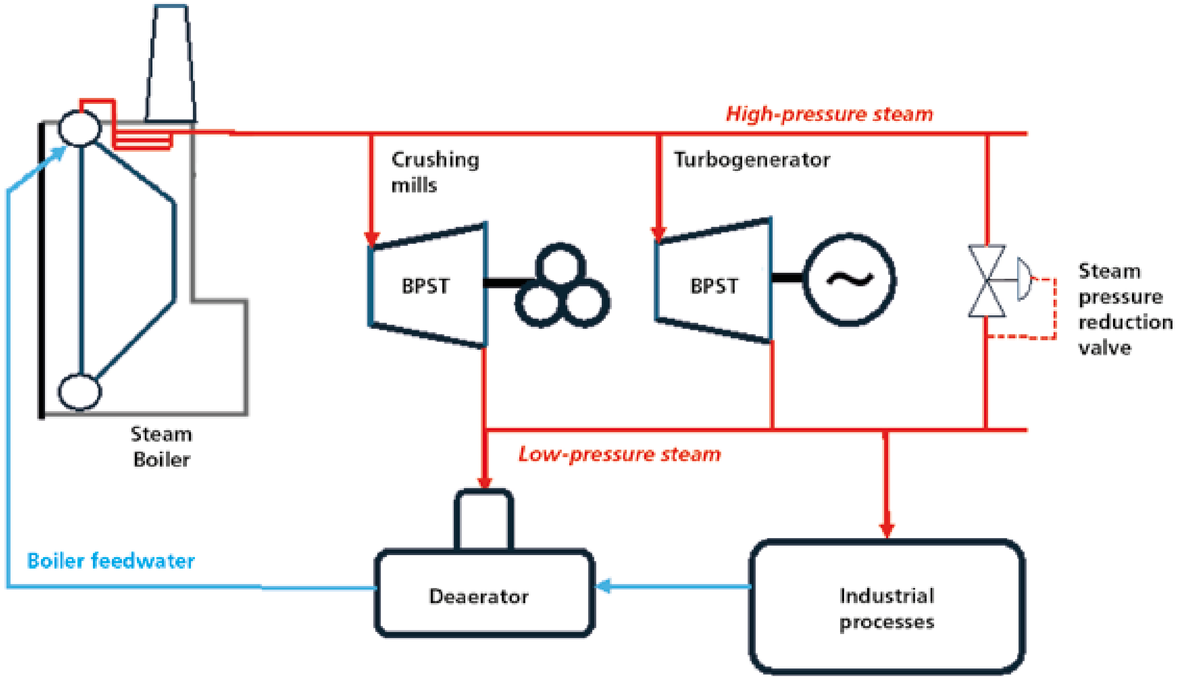
The industrial processing of sugarcane requires three forms of energy: **thermal energy** for heating and concentration processes, **mechanical energy** for operations such as milling, pumps, and fans, and **electrical energy** for process control, monitoring systems, lighting, amongst other uses.

6.1.1. Basic cogeneration systems in sugarcane processing mills

To meet their energy needs, sugarcane mills have developed systems for generating their own energy, using the available solid biofuels and, historically, due to limitations in public electricity distribution networks. These systems use steam turbines to generate different forms of energy simultaneously in a cascading process. This highly efficient method has advanced significantly in recent years and has greatly expanded bioelectricity generation. This technology, known as cogeneration, gives sugarcane a key advantage over other raw materials used for producing sugar or bioethanol as they typically require external energy sources for industrial processing.

Figure 48 shows a basic schematic diagram (not including the boiler feed pumps) commonly used in cogeneration systems across the global sugarcane industry. In summary, the heat produced from burning bagasse in boilers generates high-pressure steam, which is used to power backpressure steam turbines in turbogenerators and to power the mills directly. The low-pressure steam is then used to meet the thermal energy requirements for processing sugarcane juice into sugar and bioethanol.

FIGURE 48. Basic schematic diagram of the cogeneration system in the sugarcane industry using backpressure steam turbines (BPST) to power the mills and the turbogenerator



Source: Prepared by the authors.

6.1.2. Steam balance in sugarcane mills

Under typical conditions, the steam balance in a sugarcane-processing mill must be carefully maintained, meaning that the steam produced should sufficiently meet the energy demands. As mill operations have evolved over time, cogeneration systems have adapted to maintain this balance by improving the efficiency of steam generation and usage. These efficiency improvements offset the increase in the amount of sugar to be processed and the decrease in fibre content in sugarcane, which has resulted from the development of improved sugarcane varieties.

Considering representative figures from Brazilian mills in the 1980s, similar to those in other countries, the availability of bagasse (with 50% moisture content) from processing one tonne of sugarcane is around 250 kg, which can produce between 500 kg and 600 kg of steam—comparable to the consumption in the process, which ranges from 400 kg to 600 kg of steam. In this context, with responsible management of steam demands and the adoption of more efficient boilers, it is even possible to generate surplus bagasse. However, the most significant gains occur in the steam turbines, which precede the use of steam in the process and result in the generation of excess electrical energy.

These gains are possible due to the flexibility provided by the high-pressure steam produced in the boilers that feed the steam turbines. While the steam pressure at the turbine outlet is generally around 2.5 bar (absolute pressure) due to the demands of the industrial process, the inlet conditions for the turbines can be selected from a wide range depending on the type of boiler used. This selection leads to power generation that is proportional to the steam's pressure and temperature as it exits the boiler. By adopting boilers and turbines that operate with steam at higher pressures and temperatures, it is possible to increase bioelectricity production in cogeneration systems without significantly changing the amount of fuel used.

Over the past few decades, the parameters for high-pressure steam have been progressively increased in Brazilian mills, an evolution also observed in other countries in Latin America and Africa that process sugarcane using technologies similar to those adopted in Brazil. Until 1980, Brazilian mills operated with boilers that had pressures between 12 bar and 22 bar and purchased about 40% of their electricity. By 1990, with the gradual replacement of older boilers and turbines, the average steam pressure in these mills reached 22 bar, with temperatures of 300°C, which was sufficient to achieve self-sufficiency in electricity supply and generate some surplus for sale. Typically, the mills consume about 28 kWh of electricity per tonne of processed cane, with approximately 16 kWh per tonne used for the preparation and milling of the cane and around 12 kWh per tonne generated as bioelectricity (Macedo, 2006). Thus, levels of self-production above this amount enable the generation of surplus bioelectricity.

Currently, in a sugar and bioethanol mill operating under typical conditions in Brazil's Central-South region, which processes two million tonnes of sugarcane annually. Conventional cogeneration systems, which operate at 65 bar and 500°C, can generate an installed capacity of 31 MW. These systems fulfil the mill's energy requirements and export around 114 GWh per year to the power distributor (Walter & Nogueira, 2010).

This basic design, featuring backpressure turbines for bioelectricity generation and driving the mills, encompasses various construction variants that allow for increased bioelectricity production per tonne of processed sugarcane. While this naturally entails investments, steam generation efficiency can be improved by utilising boilers with suspended combustion, incorporating preheating systems for the combustion air and boiler feed water, as well as reducing process steam consumption and enhancing condensate recovery. However, the most significant improvements can be made by increasing boiler pressure, adopting more efficient steam turbines and electrifying the mills, as discussed below.

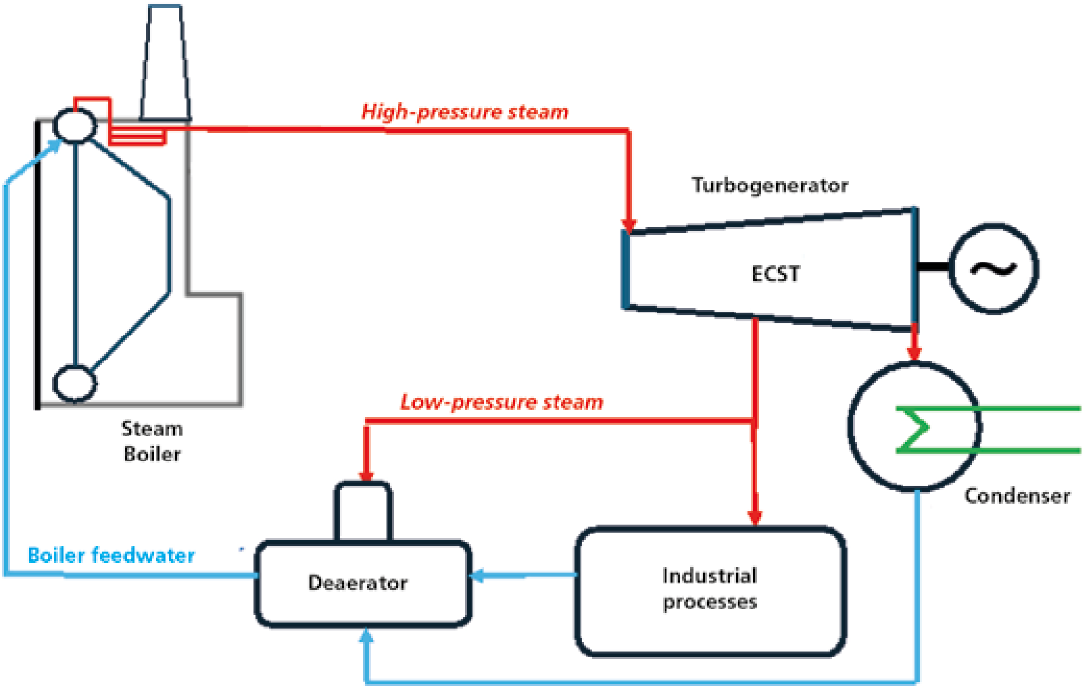
6.1.3. Improved cogeneration systems in sugarcane processing mills

Over the past few decades, there has been significant expansion in the use of more efficient setups for cogeneration systems in sugarcane processing mills in Brazil, greatly increasing bioelectricity generation. The development of the regulatory framework in the electricity sector has served as the main impetus for this cycle of innovation, allowing self-producers to sell their excess bioelectricity to the public grid and generating significant economic gains. Whilst in 2005 the sale of bioelectricity accounted for nearly 1% of the mills' financial performance, by 2015 it had risen to 16% (COGEN, 2024).

With the capacity to sell surplus bioelectricity, sugar and bioethanol mills also began to place greater value on the solid residues from harvesting, such as sugarcane straw. Traditionally, these residues were burned in the field to facilitate sugarcane harvesting. However, due to environmental regulations, there has been a gradual shift towards harvesting unburned sugarcane—meaning no pre-harvest burning—, which has increased the availability of fuel for the boilers and, consequently, boosted bioelectricity generation.

Under these conditions, cogeneration systems have evolved into the configuration shown in Figure 49, with boilers operating at high pressure and feeding multi-stage extraction/condensation steam turbines. These turbines drive turbogenerators with outputs in the tens of megawatts, achieving over 70% efficiency in steam usage. In this configuration, the mills are powered by electric motors with variable speed, using frequency inverters and digital control, offering better performance and lower steam consumption compared to conventional direct drives using backpressure steam turbines, the efficiency in steam utilisation of which is below 50%.

FIGURE 49. Schematic design of the cogeneration system in the sugar and ethanol industry, using extraction/condensing steam turbines (ECST) in the turbo generator and electric motors to power the mills



Source: Prepared by the authors.

Table 14 illustrates the importance of steam production conditions, steam consumption during the process, and the utilisation of sugarcane straw in the boilers for generating energy surpluses (electricity and bagasse) in sugar and bioethanol mills, with results presented per tonne of sugarcane (tc). These estimates are based on the production of 280 kg of bagasse (with 50% moisture) for each tonne of sugarcane, using steam at a pressure of 2.5 bar and employing backpressure steam turbines. However, in scenarios where operations are assumed to take place outside the harvest season or when process steam consumption is low, the use of condensing turbines is considered, with the condenser operating at 0.12 bar absolute. When the use of straw is considered, it is assumed that 50% remains in the field, leading to an effective availability of 70 kg of this biofuel per tonne of sugarcane harvested.

TABLE 14. Bioelectricity and surplus bagasse in cogeneration systems in the sugarcane agroindustry

STEAM PRESSURE AND TEMPERATURE AT THE BOILER OUTLET	PROCESS STEAM CONSUMPTION (KG/TC)*	GENERATION PERIOD	USE OF STRAW	SURPLUS ELECTRICITY (KWH/TC)*	SURPLUS BAGASSE (KG/TC)*
21 bar, 300°C	500	Harvest	No	10	33
42 bar, 400°C	500	Harvest	No	25	50
42 bar, 450°C	500	Harvest	No	28	48
65 bar, 500°C	500	Harvest	No	58	13
65 bar, 500°C	350	Harvest	No	72	0
65 bar, 500°C	500	Year-round	50%	140	13
65 bar, 500°C	350	Year-round	50%	153	0
80 bar, 520°C	350	Harvest	No	100	
90 bar, 520°C	400	Harvest	No	146	0
105 bar, 525°C	280	Harvest	No	158	0

*TC: Sugarcane tonne
Source: BNDES & CGEE (2008) and Seabra (2008).

As shown in the table, increasing the exportable surplus of bioelectricity is closely linked to higher pressure levels. Furthermore, in the context under consideration, reducing process steam consumption from 500 kg to 350 kg per tonne of sugarcane processed results in a 24% increase in bioelectricity surplus. Additionally, with partial use of sugarcane straw, the energy surplus increases by 141%.

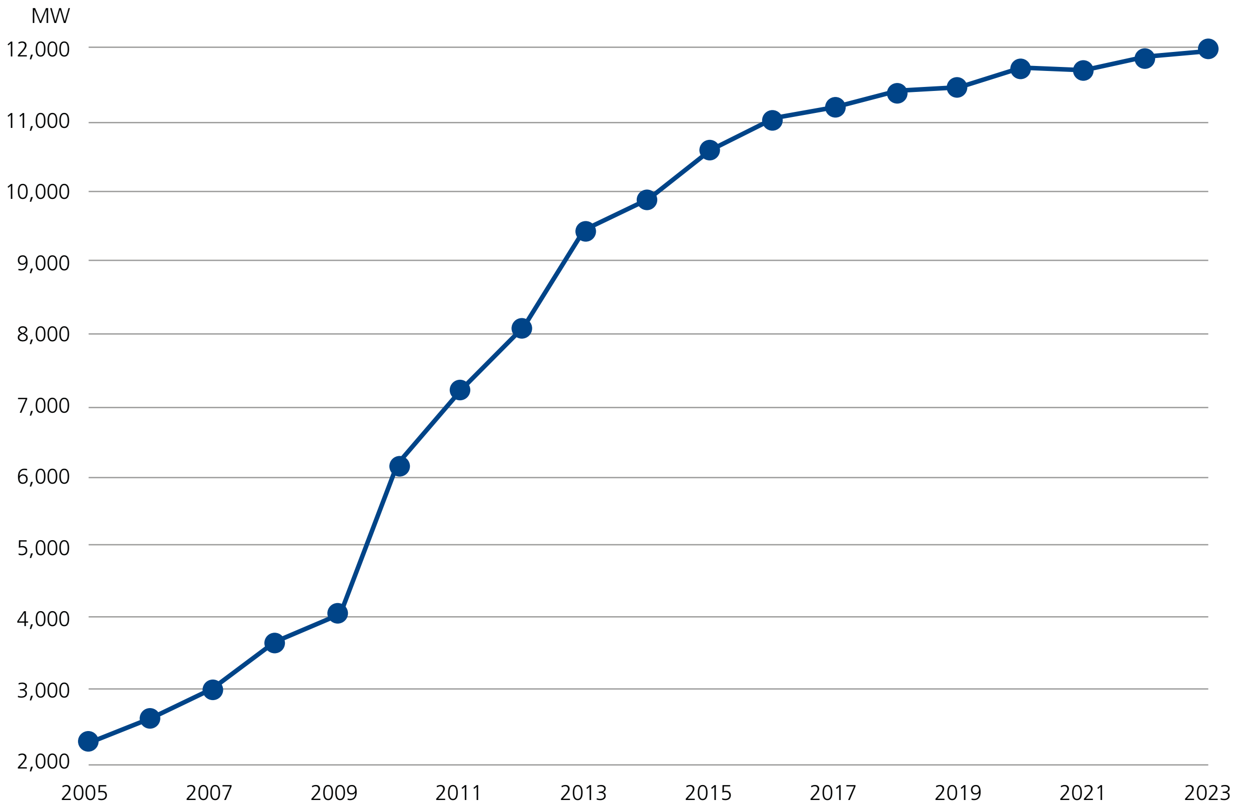
Despite the potential for significant energy gains through the use of high steam parameters in cogeneration systems, opting for higher pressures to increase surplus bioelectricity generation entails substantial investments, particularly due to the need for more sophisticated treatment of boiler feed water. Consequently, the economic viability of cogeneration projects depends, among other variables, on the tariff structure, the regulatory framework and the prospects and types of contracts with the electricity sector—factors that are fundamentally external to the usual operations of the mill.

When evaluating the contexts of higher efficiency and productivity of bioelectricity in the sugarcane agroindustry, it is important to understand the limits of these energy conversion processes. Specifically, how much bioelectricity could be effectively produced from one tonne of sugarcane, a crop known for its high efficiency in solar energy conversion, as discussed earlier in this work. In an assessment of various future energy conversion possibilities in the sugarcane agroindustry, combining different products and technological pathways—including the gasification of bagasse and the use of gas turbines—Lora *et al.* (2014) concluded that it would be technically feasible to generate 511 kWh from one tonne of sugarcane during the harvest season or 366 kWh throughout the year. When compared to the data in the previous table, these figures highlight the significant potential for advancing cogeneration systems.

6.1.4. Cogeneration indicators in sugarcane processing mills in Brazil

As of December 2023, the cogeneration plants installed in Brazil's sugar and bioethanol mills using bagasse and sugarcane straw as fuel amounted to 12 GW of installed capacity. These facilities account for 6% of Brazil's total electricity generation capacity and make up 60% of the country's installed capacity in cogeneration systems.

GRAPH 32. Evolution of installed generation capacity in cogeneration systems within Brazil's sugarcane industry

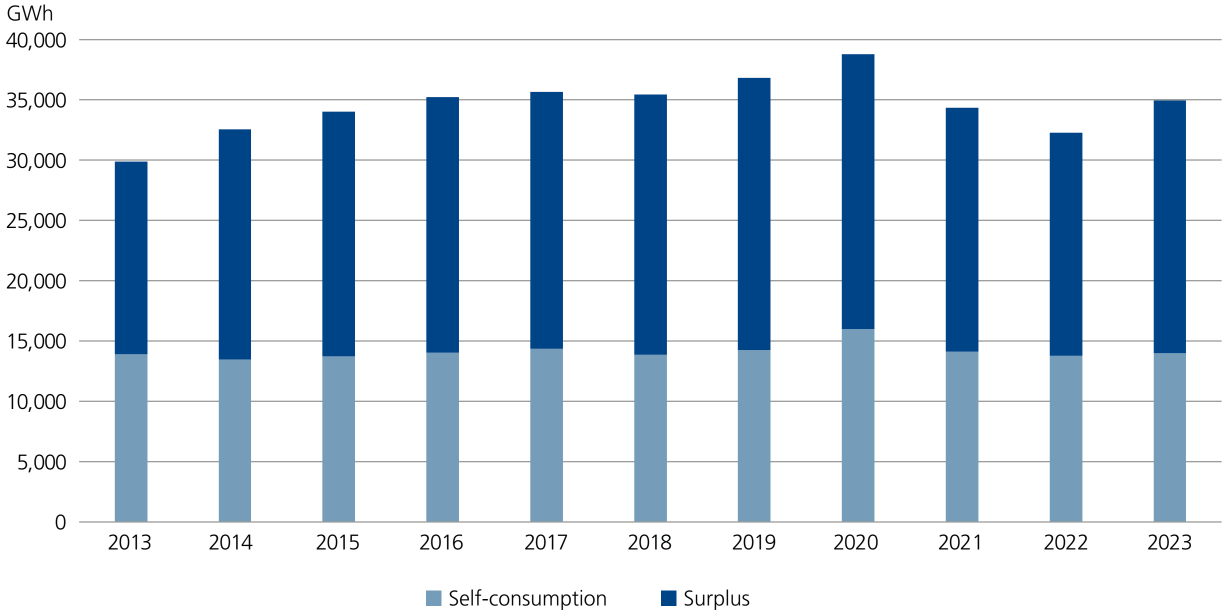


Source: EPE (2024a).

As shown in Graph 32, cogeneration using sugarcane biomass expanded rapidly between 2005 and 2015, with installed capacity growing at annual rates above 17%, aimed at generating and selling surplus energy. According to the Brazilian Electricity Regulatory Agency (ANEEL), an additional 1.6 GW of cogeneration systems in sugarcane mills is expected to begin operating by 2026 (COGEN, 2024).

In 2006, cogeneration in sugarcane mills accounted for 2% of Brazil's electricity production, a share that reached 6% in the years leading up to the COVID-19 pandemic. In 2023, these systems injected a total of 21 GWh into the public grid, around 60% of the total bioelectricity produced at the mills, with the remainder consumed in industrial processes, as indicated in Graph 33. That year, excluding the portion used for self-consumption at the mills, electricity generation from bagasse and straw amounted to 29.3 kWh per tonne of sugarcane (COGEN, 2024). A large share of this generation is concentrated in the country's Centre-South region.

GRAPH 33. Self-consumption and surplus bioelectricity in Brazil's sugarcane agroindustry



Source: EPE (2024a).

The 2031 Ten-Year Energy Expansion Plan, presented by the Energy Research Office (EPE), highlights the potential of bioelectricity generation from bagasse and sugarcane straw as a competitive source of supply for Brazil's National Interconnected System. The study estimates that the average power delivered by the mills to electric utility companies in 2021, 2.6 GW, is expected to reach 4.1 GW by 2031, with a technical potential of 6.2 GW in that year (EPE, 2022).

An important characteristic of bioelectricity from sugarcane in Brazil is its complementarity with hydropower generation, which dominates the country's electricity matrix. The supply of surplus bioelectricity from mills in the Centre-South of Brazil is considered non-intermittent and occurs during the sugarcane harvest, from March to October, coinciding with the dry season in the region and lower availability of energy from hydropower plants. This contributes to increasing the electricity supply to the national grid, preserving the energy stored in hydroelectric reservoirs and reducing the need for fossil fuels in conventional thermal power plants. During the dry season in 2023, cogeneration in the sugarcane sector covered 14% of the electricity consumption in the Centre-South region and avoided the emission of 4.3 million tonnes of CO_2 (UNICA, 2024).

In this regard, it is important to note that, in terms of energy efficiency, cogeneration is far superior to conventional thermal generation. These thermal power plants typically convert around 30% of the energy provided by the fuel into useful energy, and under extreme conditions, may convert up to 50%, inevitably rejecting a significant portion of thermal energy into the environment. Cogeneration systems, by using the rejected heat to meet process thermal needs, achieve efficiencies of over 85% in fuel energy usage, resulting in evident benefits for cost-effectiveness and reduced environmental impacts.

6.2. Use of vinasse and filter cake for the production of biogas and biomethane

This section is based on a report prepared for this book by Bruna de Souza Moraes from the Centre for Energy Planning, University of Campinas (UNICAMP).

Biogas production is a relatively recent innovation in Brazil's sugarcane industry, offering both environmental and energy-related benefits. By-products of sugarcane processing, such as vinasse and filter cake—often wrongly referred to as waste—serve as the raw materials for anaerobic digestion in this context. Through this biological process, which occurs in the absence of oxygen, these effluents are converted into biofertiliser, highly beneficial for sugarcane crops, and biogas.

Biogas is a combustible gas composed of 45% to 75% methane (CH_4), along with carbon dioxide (CO_2) and low levels of hydrogen sulphide (H_2S). It can be used directly in boilers at the mills. Furthermore, biogas can be purified to increase its methane content to over 90%, at which point it is known as biomethane (regulated by the Brazilian National Agency of Petroleum, Natural Gas and Biofuels—ANP) (ANP, 2017). With a composition very similar to natural gas biomethane can be used as vehicle fuel or distributed through natural gas networks. By replacing fossil fuels, biomethane can reduce greenhouse gas emissions by up to 95%.

The use of vinasse as a fertiliser has been practised in Brazilian mills since the 1980s, prompted by environmental legislation prohibiting its discharge into water bodies. Rich in potassium, vinasse is applied to sugarcane fields, recycling nutrients contained in the cane and reducing the need for commercial fertilisers. Biogas production reduces the toxicity of vinasse while preserving its valuable nutrients for sugarcane cultivation, making it easier to use as fertiliser, in a process called “fertirrigation”. However, vinasse also contains high levels of organic matter, which can lead to greenhouse gas emissions when spread on the fields.

6.2.1. Anaerobic digestion and its products

As early as the 18th century, Alessandro Volta discovered that the decomposition of organic matter in the absence of oxygen, as seen in marshes, produces a combustible gas: methane. In an effort to replicate this process under controlled conditions, the first anaerobic digesters were constructed in the early 20th century to treat agricultural and agro-industrial waste, thereby reducing their environmental impact while generating biogas. With improvements in digester technology and a better understanding of the biological processes involved, anaerobic digestion began to be adopted for the treatment of urban and industrial effluents.

From the 1980s onwards, with a heightened focus on sustainability and the expansion of modern energy services in remote areas, simplified small-scale anaerobic digesters, fed with animal waste, were widely adopted in rural regions of Asian countries, particularly India and China, to produce biogas. In developed countries, anaerobic digestion became established with the use of progressively larger reactors, featuring temperature control and systems for stirring and recirculating organic material, capable of processing high loads with great efficiency in biogas generation. In both contexts, this technology serves two complementary purposes: producing a renewable fuel and enabling effective waste management, thereby reducing landfill loads and protecting water quality, with lower greenhouse gas emissions than natural decomposition.

In 2018, global biogas production reached approximately 180 billion cubic metres (m^3), equivalent to 35 million tonnes of oil equivalent (Mtoe), accounting for about 2.5% of the world’s total natural gas production. This output represents only 4.8% of the global potential for biogas (as biomethane), with estimates suggesting that the availability of sustainable raw materials could allow biogas production to grow by 40% by 2040 (IEA, 2020). For electricity generation, it is estimated that in 2020, 90 GWh were produced globally from biogas (REN21, 2024). These figures indicate that anaerobic digestion is already significant in the global energy landscape and has the potential for further growth.

Biogas production systems also enable the generation of value-added bioproducts, such as digestate (the liquid effluent from the digester with fertilising properties), biomethane (a biofuel similar to natural gas), biogenic CO_2 (derived from purifying biogas to biomethane), along with other potential intermediate bioproducts from the process, including organic acids, alcohols and hydrogen.

6.2.2. Anaerobic digestion in the sugarcane agroindustry

Vinasse is the liquid effluent generated during the distillation of bioethanol from any source, typically produced at a rate of 10 to 15 litres for every litre of bioethanol. Depending on the technology applied and the operational conditions of the digesters, from 10 to 26 cubic metres of biogas can be produced from one cubic metre of vinasse, with an average methane content of around 60%.

Focusing solely on the production of ethanol from sugarcane, a context in which the adoption of anaerobic digestion has been increasing, the annual volume of vinasse available—approximately 342 million m^3—could yield around 6.2 billion m^3 of biogas. If purified, this volume of biogas translates to about 4.1 billion m^3 of biomethane, which represents 20% of Brazil's total natural gas consumption in 2022 (EPE, 2023b). Projections for the next decade estimate that the potential production of biomethane could grow by over 20%, reaching 6.1 billion Nm^3, assuming the total utilisation of vinasse, filter cake, and 20% of leaves and tops. Importantly, the production of biogas from vinasse does not interfere with its use in fertigation systems as the digestate (the liquid effluent from the digester) can be used to recycle nutrients, particularly potassium, for the sugarcane fields.

However, the digestion of vinasse presents challenges, particularly due to its complex and variable characteristics: it has a high organic content, elevated acidity (pH between 3.5 and 5), a relatively high carbon-to-nitrogen (C/N) ratio (between 15 and 30) and a composition that varies throughout the harvest season depending on the sugarcane processed and the production processes of the mill. These factors complicate the maintenance of operational stability in the digesters. Generally, vinasse is available at high temperatures (80 to 90°C) as it exits the distillation columns, allowing digesters to operate in the thermophilic range for optimal performance (around 60°C), though this necessitates temperature control systems.

Moreover, vinasse from sugarcane bioethanol is not produced during the off-season (approximately 4–5 months). During this period, commercial operations typically involve shutting down the digester or biological reactor, which remains dormant. This downtime results in significant efficiency losses within the system, which must undergo a start-up and adaptation phase to the biological process at the beginning of each harvest. These losses are well-known and highlight the need for advancements in the maturation of technology and the application of existing scientific knowledge.

Indeed, there have been notable advancements in more efficient systems for anaerobic digestion of sugarcane vinasse, employing high-efficiency reactors (such as upflow anaerobic sludge blanket—UASB, and continuous stirred tank reactor—CSTR) or co-digestion with other substrates, which are beginning to gain traction. In addition to enhancing system efficiency, these solutions involve the integration of substrates within the context of biorefineries and are highly promising.

This includes the co-digestion of vinasse with filter cake, a solid by-product derived from filtering the juice extracted from crushed sugarcane. This method can enhance methane production yields by over 60%, depending on the technology employed, while also reducing or potentially eliminating the need for alkalinisers in the reactor, which are necessary for the digestion of pure vinasse (Gonzalez *et al.*, 2017; Volpi *et al.*, 2021). Each tonne of crushed sugarcane generates between 25 and 40 kg of filter cake, and for every tonne of filter cake, there is the potential to produce 105 m^3 of biogas. Table 15 presents various data and process parameters related to biogas production using substrates from sugarcane mills in efficient reactors.

TABLE 15. Parameters for biogas production using substrates from the sugar-energy sector

REACTOR TYPE	ORGANIC LOAD RATE (KGCOD/ M^3/DAY)	METHANE PRODUCTIVITY (M^3/KGCOD)	HYDRAULIC RETENTION TIME (DAYS)	EFFICIENCY (%COD REMOVAL)	REFERENCE
Fundamental research at lab scale, processing vinasse plus filter cake					
s-CSTR	4.16	0.25	14	-	Volpi *et al.*, 2021
UASB	45	0.20	1	-	Barros *et al.*, 2017
Fully commercial scale, processing vinasse					
UASB	10.5	0.22	4.9	89	Craveiro *et al.*,1986
UASB	18.3	0.47	0.8	76	Costa *et al.*,1986
UASB	26.5	0.42	0.5	72	Souza *et al.*,1992

Note: COD is the Chemical Oxygen Demand, a measure of the organic load of a substrate.
Source: Prepared by the authors.

Other by-products from sugarcane processing, such as bagasse and straw, also hold potential for biogas production (200 to 220 m^3 of biogas per tonne). However, because these are lignocellulosic materials, they require pre-treatment similar to that used for producing cellulosic ethanol. This adds to the investment costs and technical complexity of the system. Moreover, the use of bagasse and straw for electricity generation is already well established, as discussed in the previous section.

Over the past decade, Brazil's maize ethanol production has expanded significantly. In the flex route, where maize is processed similarly to sugarcane, maize vinasse (known as thin stillage) is generated, which has potential for biogas production and could be utilised during the sugarcane off-season. In the full route, which has become more widely adopted, the vinasse is incorporated into the fermentation effluent and dried for animal feed production (dried distillers grains with solubles—DDGS). Nevertheless, the potential for biogas production from this route has been minimally explored in Brazil.

Beyond the bioenergy industry, manure is considered an interesting co-substrate for biogas production alongside vinasse and could be applied during the sugarcane off-season. Additionally, manure can reduce or even eliminate the need for alkalinisers. However, logistics must be considered, as significant volumes of this co-substrate may be required feeding a biodigester in sugarcane mills.

6.2.3. Perspectives of anaerobic digestion in the sugarcane agroindustry

Despite the abundant availability of substrates and co-substrates, the installed capacity of biogas plants in the sugar-energy sector still has significant room for growth, with less than 5% of the potential biogas from vinasse and filter cake being effectively produced (EPE, 2023c). From a technological standpoint, there is also scope for the adoption of more efficient processes. Although biogas production systems from vinasse were first documented in the 1980s (Craveiro *et al.*, 1986; Costa *et al.*, 1986; Souza *et al.*, 1992), most biological reactors installed to date still consist of covered lagoons—an inexpensive, simple, but inefficient technology that is an adaptation of vinasse stabilisation ponds.

However, more efficient systems are gradually being adopted by some mills, combining anaerobic lagoons for the initial treatment of vinasse with continously stirred tank reactors (CSTR), known as vertical biodigesters, for co-digestion with filter cake. In this context, the work of Geo bio gas&carbon, a company founded in 2008, has been instrumental in promoting modern anaerobic digestion technologies and driving new ventures. By mid-2024, the company operated three plants at sugarcane processing mills, with a total of 36 MW of installed electrical generation capacity and the ability to produce 75,000 Nm^3/day of biomethane. Additionally, they had four plants under construction aimed at decarbonising the mills' operations, which are expected to produce 205,000 Nm^3/day of biomethane by 2025.

The biomethane produced by these projects—equivalent to 296,000 litres of diesel per day—alongside electricity generation, will undoubtedly aid establish biogas in Brazil's energy matrix by utilising a renewable energy resource that has been largely untapped until now. Below are two projects of this type (Geo bio gas&carbon, 2024).

FIGURE 50. Geo Elétrica Tamboara biogas plant

Photo: Alessandro Gardemann/Geo bio gas&carbon.

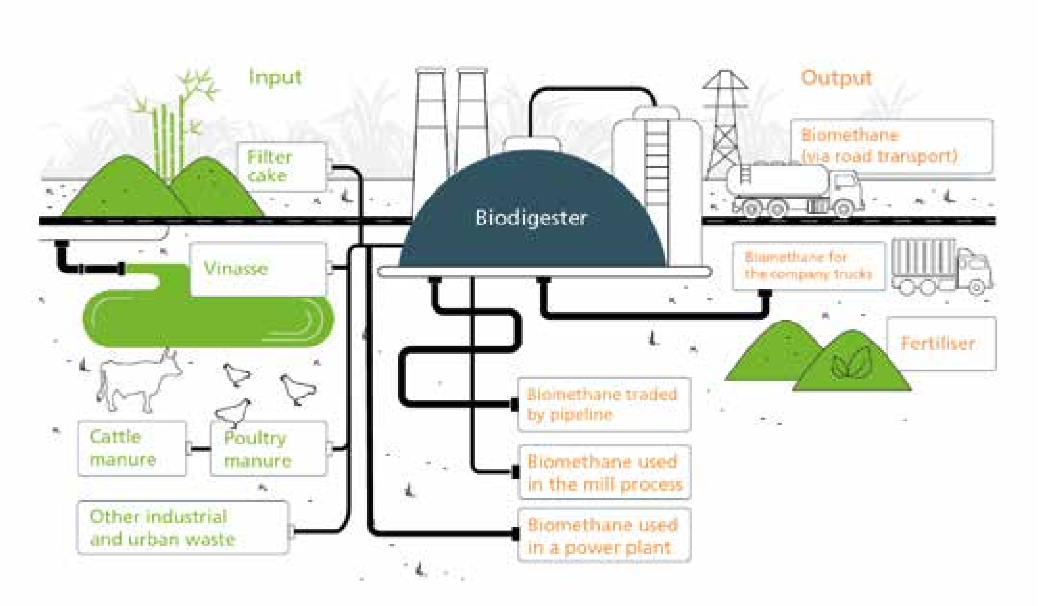
Geo Elétrica Tamboara, located in Tamboara, Paraná, was Brazil's first large-scale commercial biogas plant to process filter cake, vinasse and straw. Construction began in 2010, and the plant was inaugurated in 2012, with an installed capacity of 10 MW for electricity generation. After winning the first auction by ANEEL to purchase energy generated from biogas, the plant has been supplying energy to the Brazilian national grid since 2016. A recent expansion increased its production to 40,000 Nm^3/day of biomethane, equivalent to 38,000 litres of diesel, which is sold as compressed natural gas to industries in the Londrina region.

Another important example is the Cocal plant, located in Narandiba, São Paulo, which processes 5.2 million tonnes of sugarcane annually. In 2021, it began operating a biogas plant that treats vinasse and filter cake, supplemented with bovine and poultry manure, producing 33.1 million m^3 of biogas and 1.6 million tonnes of biofertiliser annually. With an installed capacity of 5 MW of electricity, the plant is expected to sell 33 GWh/year, along with producing 26,000 Nm^3/day of biomethane. Part of this biomethane powers the plant's fleet, replacing diesel, while the remainder is sold regionally and injected into the Necta (formerly Gas Brasiliano) pipeline network, the natural gas distributor in this area.

The Cocal biogas plant consists of four horizontal reactors (covered lagoons), each with a capacity of 18,000 Nm^3, fed exclusively with vinasse, and two vertical CSTR reactors of 8,000 Nm^3 each, fed with both vinasse and filter cake.

This system processes 80% of the total vinasse produced, with the remaining portion being spread directly onto the sugarcane fields. The fertigation process adheres to the Environmental Company of the State of São Paulo (CETESB) regulations, particularly concerning potassium levels in the soil (CETESB, 2006).

FIGURE 51. Flowchart of the biogas production proposal at the Cocal plant



Source: Adapted from Cocal (2025).

FIGURE 52. Aerial view of the Cocal plant, consisting of four horizontal reactors (covered lagoons) and two vertical reactors (CSTR)

Photo: Alessandro Gardemann/Cocal.

At this plant, during the sugarcane off-season, when vinasse is not produced, biomass from external sources, such as cattle and poultry manure, is used to feed the vertical reactors to maintain biogas production. The horizontal reactors reduce their activity during the off-season. The biomethane production system employs chemical and biological H_2S removal processes, followed by a pressure swing adsorption (PSA) unit with an activated carbon system to remove CO_2. The recovered CO_2 is sold as a by-product to the drinks industry.

As of June 2024, there were 24 registered plants with ANP undergoing the authorisation process to sell biomethane. If all are approved, these plants would contribute an additional 1.14 million Nm^3/day to the national biomethane production capacity (ANP, 2024c).

According to the President of the Brazilian Biogas and Biomethane Association (ABiogás) (Gardenmann, 2024), the average cost of implementing a complete biogas plant in the sugar-energy sector is *circa* BRL 9 million per MW installed. For biomethane production, the investment increases by an additional 40-60% due to the purification system.

6.2.4. Regulation and incentives

The diffusion of anaerobic digestion within Brazil's sugar-alcohol sector has been supported by stimulus measures that mitigated technological and economic risks typically associated with adopting innovations, thereby fostering an investment-friendly environment and promoting new businesses. In this context, key developments include the 2017 biomethane regulation by ANP, which was the first step towards boosting biomethane production in the country, and the ANEEL auctions for purchasing electricity generated from biogas, which secured a long-term market and sales price.

Two recent public policies deserve mention. The Future Fuel Law, mentioned in Chapter 2, mandates a growing share of biomethane in natural gas consumption, increasing from 1% in 2026 to 10% by 2034, which can be sourced either directly by distribution concessionaires or through biomethane origin guarantee certificates. The Federal Strategy to Promote the Sustainable Use of Biogas and Biomethane, created by Decree 11,003/2022, was launched, aiming to promote the use of biogas and biomethane; expand investment in infrastructure for the production, distribution and commercialisation of biogas and its derivatives; promote research related to this biofuel; and encourage the use of biomethane in public transport and biofertilisers in agriculture.

It is crucial that these mechanisms evolve alongside technological advancements grounded in economic and practical rationality. A good example of this approach is the RenovaBio programme, where biomethane consistently receives the highest energy-environmental efficiency score amongst biofuels, generating more decarbonisation credits (CBIO) per megajoule (MJ) sold compared to ethanol or biodiesel. All biomethane plants are eligible for 100% volume generation of CBIOs, a unique feature among the biofuels participating in this programme (ANP, 2024c).

With an average rating of 78.0 gCO_2e/MJ (the CO_2 emissions avoided by using biomethane) achieved by certified biomethane producers under RenovaBio (ANP, 2024c) and considering the current CBIO price of BRL 100.00 (approximately USD 20.00), the additional revenue generated from CBIO sales is estimated at around BRL 0.28 (USD 0.06) per cubic metre of biomethane.

6.3. Use of sugarcane straw: the SUCRE Project

The gradual prohibition of burning sugarcane straw prior to harvesting, currently permitted only under licence, during certain periods of the year and in areas where mechanised harvesting is not feasible due to topography was established by state and federal environmental agencies in Brazil from 2002 (SÃO PAULO, 2002). Since then, mechanised harvesting of unburnt sugarcane has become widespread, transforming straw—previously burned in the fields—into a valuable agricultural product. This shift has driven and justified significant changes in agricultural and industrial operations. For instance, manually harvested sugarcane would arrive at the mill as whole stalks and was washed to remove soil and ash from the burning process, consuming large amounts of water. However, in mechanised harvesting, the sugarcane arrives chopped and needs to be dry cleaned using air currents to prevent sugar loss. Another consequence of this increased biomass availability was the considerable expansion of cogeneration in Brazil, as previously mentioned.

On average, sugarcane fields in Brazil's Centre-South region yield approximately 120 kg (dry weight) of straw (40% cane tops and 60% leaves) per tonne of harvested cane stalks—a similar amount in dry mass to the bagasse from the cane stalks. The collection and utilisation of this biomass has introduced new challenges and questions, leading to studies aimed at evaluating the impact of straw removal and developing appropriate systems for its collection, transport and end use—biomass that remains underutilised on a global scale.

To tackle these challenges, in a learning and innovation process grounded in scientific research and experimentation and involving various field activities at sugar mills engaged with the outcomes, Brazil's National Laboratory for BioRenewable Energy (LNBR) developed the Sugarcane Renewable Electricity (SUCRE) Project. Beginning in 2015 and completed by 2020, this project aimed to increase electricity production with low greenhouse gas emissions within the sugar-energy sector by using sugarcane straw as a feedstock. The project sought to (LNBR/SUCRE, 2025):

- Overcome technological barriers to collecting and utilising straw for electricity generation in bagasse boilers.
- Assess and demonstrate the economic viability of these projects.
- Ensure that the agro-environmental impacts of removing straw from the soil are accounted for and minimised.
- Contribute to a legal and regulatory framework that encourages the generation and commercialisation of bioelectricity.
- Broadly disseminate the project's findings to encourage new initiatives interested in using straw for this purpose.

The SUCRE Project was managed in partnership with the United Nations Development Programme (UNDP) and funded by the Global Environment Facility (GEF). The key results of this project are summarised below.

6.3.1. Harvesting and transporting sugarcane straw

A significant challenge faced by the SUCRE Project was determining the appropriate amount of sugarcane straw to harvest and utilise, as well as how much should remain in the field as soil cover. Leaving some straw in the field helps to reduce soil compaction, erosion, and the proliferation of invasive plants whilst also partially recycling the nutrients necessary for sugarcane growth.

It was observed that the amount of straw available for removal depends on local factors such as soil type, topography, soil moisture and the condition of the sugarcane crop. These variables allow for mapping areas suitable for straw removal and determining rational levels for its production, adhering to soil conservation and productivity criteria.

Based on the results of straw collection experiments conducted in various climatic conditions and soil types in Brazil's Centre-South region, the project was able to establish methodologies and recommendations for the correct removal of straw. These guidelines assist in deciding the quantity, timing and location of straw removal, as well as identifying areas suitable, unsuitable, or restricted for the removal of this biomass (LNBR, 2019a; LNBR, 2019b). On average, it is recommended that between 40% and 60% of the straw be left as soil cover once the sugarcane has been harvested.

For the harvesting and transportation of sugarcane straw, two systems were studied within the SUCRE Project:

- **Integral recovery**: In this method, the straw is harvested, chopped and transported along with the sugarcane stalks from the field to the mill, where it is separated from the stalks before milling.
- **Separate recovery**: In this approach, the straw is left in the field for about two weeks after the sugarcane harvest to reduce its moisture content. It may or may not be baled before being collected and transported, allowing it to be compacted into bales for transport to the mill.

FIGURE 53. Straw shredder attached to a sugarcane harvester

Photo: CNPEM.

The performance of these straw recovery systems depends on various factors such as logistics systems, transportation distances and costs, terrain topography, soil characteristics and climatic and agronomic conditions, which vary in each case and context. Each system has its advantages and challenges, necessitating a specific evaluation of the location to select the best option.

Integral recovery of the straw along with the sugarcane stalks results in a lower load density in transportation trucks, significantly impacting costs, which depend on the distance between the sugarcane field and the mill. Another issue identified is the low efficiency of dry-cleaning systems, which are essential for integral recovery to ensure effective processing of the stalks at the mill.

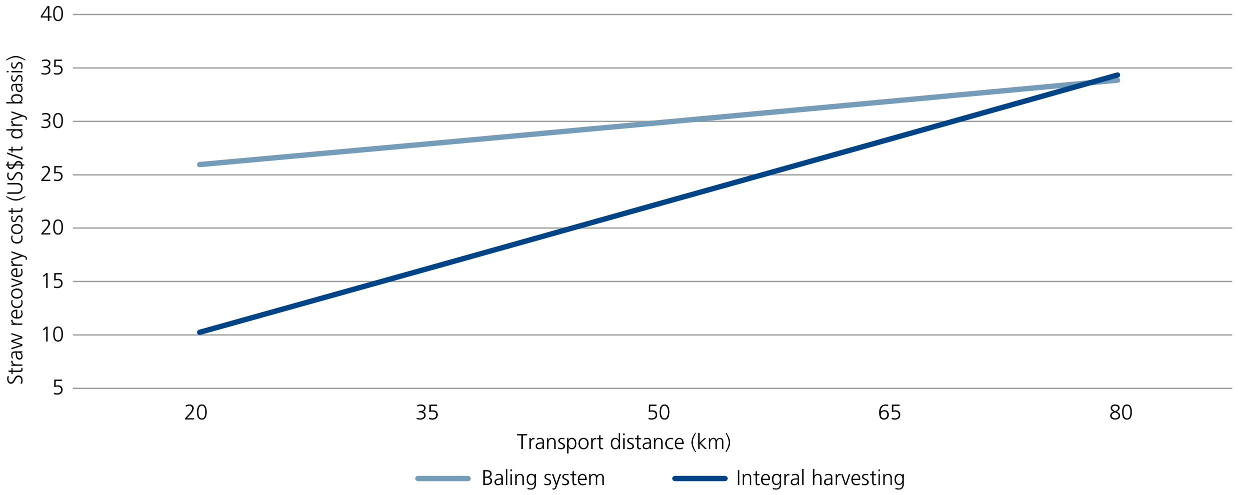
Given this, the Sugarcane Technology Centre (CTC), as partner of the SUCRE Project, developed a shredder that can be attached to a sugarcane harvester, reducing the size of the straw and helping to separate the portion of straw that should remain on the soil. The results of tests conducted with this equipment were promising, leading to increased load density and a consequent reduction in transportation costs for sugarcane with straw, as well as improved efficiency in separating the straw at the mill (LNBR, 2018a).

FIGURE 54. Sugarcane straw (tops and leaves) left on soil after sugarcane harvest

Photo: CNPEM.

In turn, separate recovery of straw has little effect on the processing of the sugarcane stalks but presents other difficulties. Harvesting the straw that is scattered on the ground necessitates its windrowing (*i.e.*, the accumulation of straw from one or more inter-rows of sugarcane), and especially in conditions of higher humidity, more soil is gathered, making cleaning it for use more laborious. If the sugarcane is compacted to reduce transportation costs, systems for baling in the field and de-baling at the mill are required, involving more agricultural operations and costs. Therefore, the separate recovery of straw can become quite expensive, as indicated in Graph 34, which presents the costs for each system as observed in São Paulo, Brazil (Cardoso *et al.*, 2018).

GRAPH 34. Cost of recovering sugarcane straw in relation to transportation distance in São Paulo, Brazil



Source: Cardoso *et al*. (2018).

6.3.2. Use of sugarcane straw

With the development and gradual adoption of systems for recovering sugarcane straw, significant volumes—amounting to several million tonnes per year—have become available. This opens economic opportunities for its use in various areas, such as fuel and raw materials, for instance, in the production of cellulosic bioethanol. However, it is essential that the straw is suitable for its intended applications.

Aiming to promotes the use of sugarcane straw as fuel in boilers, the SUCRE Project has highlighted challenges associated with burning straw as it is brought from the fields. These challenges are linked to the high content of mineral impurities and the presence of harmful elements that adversely affect the efficient operation of the boilers, such as chlorine, sulphur and potassium. Moreover, regardless of the recovery system employed, the straw arrives at the processing plant with a particle size distribution that differs significantly from that of bagasse. This, in turn, complicates the feeding process into the furnaces and reduces the combustion efficiency of the mixture in the boilers. In summary, the project has demonstrated that the presence of mineral impurities, harmful elements and particle size distribution make sugarcane straw very different from bagasse, which is the fuel on which Brazilian boilers were designed to run.

As Brazilian mills continue to operate boilers with considerable remaining service life, and as the procurement of new boilers specifically designed for straw combustion is still under consideration, the SUCRE Project assessed the feasibility of using straw in the current boilers. To this end, the approach involved modifying the properties of the straw, blending it with bagasse and burning the resulting mixture in boilers. This strategy aimed to replicate the operating conditions experienced with bagasse whilst also lowering the operational costs of the existing equipment.

In four mills, systems for processing straw for boiler use were developed and implemented based on field assessments and laboratory findings. The straw undergoes a dry-cleaning process, is washed with water using mechanical agitation, treated, and the water is recycled prior to being ground together with the cane during the final pass through the mills. Under optimised operating conditions, the resulting particle sizes suitable for combustion in the existing boilers were attained, as illustrated in Figure 55. There were also significant reductions in ash content (74% less) and critical chemical elements: chlorine (93% less), sulphur (16% less), potassium (82% less), and silicon (62% less), all measured by mass on a dry basis (LNBR, 2019c). Remarkably, efficiency measurements indicated that boilers burning mixtures of bagasse and straw achieved gains of approximately 2% (LNBR, 2018b).

FIGURE 55. Bales of sugarcane straw ready to be transported to the mill

Photo: CNPEM.

In its work focused on economic assessment, the SUCRE Project developed a methodology to evaluate the economic viability of collecting and using sugarcane straw for electricity generation in mills. This methodology is based on agricultural, industrial and market parameters for the sale of electricity. The model was customised for the specific operational conditions of each mill, and in most simulated cases, electricity prices were observed that enable the use of straw as a supplement to bagasse for electricity generation during the sugarcane harvest under various selling alternatives. As noted in the section on cogeneration, the higher electricity prices during the sugarcane harvest favour the economic viability of employing straw.

Amongst the various documents and tools made available free online by the SUCRE Project, the following should be mentioned (LNBR/SUCRE, 2025):

- PalhaCalc: An online and free tool for studying the economic viability and environmental benefits of a project for recovering sugarcane straw for electricity generation. The calculations use parameters provided by the user, such as collection routes, the amount of straw to be collected, and specific steam production from bagasse in the boilers, amongst others.
- Other SUCRE Project booklets: *Sugarcane Straw Recovery Routes*, *Sugarcane Straw Processing and Burning*, *Sustainable Bioelectricity*, and *Bioelectricity Booklet*.

The recovery and utilisation of sugarcane straw is a relatively recent development in this agribusiness, with significant advancements and evident environmental and economic benefits. This technology can and should be evaluated for other sugarcane-producing countries that still practice pre-harvest burning. This waste of energy will soon be considered outdated and fortunately overcome, just as we now view the use of firewood in the old sugar mills.

6.4. Circularity in maize ethanol production

This section is based on a briefing prepared by Claudia Domingues Romeiro Shirozaki and Rubiane Maria Jacobowsky from FS Fueling Sustainability.

The previous sections addressed the integration of processes and diversification of final products, such as bioelectricity, biogas and straw in bioenergy production chains, focusing on processes involving sugarcane. The long history of sugarcane industrialisation in Brazil and the adoption of bioethanol as a vehicle fuel since the early part of the last century justify the chosen approach. However, the production of maize bioethanol, which has recently been implemented successfully in Brazil, also presents very interesting sustainability indicators, particularly in terms of circularity.

Situated within the broader concept of sustainability, circularity has received an extensive definition from the World Business Council for Sustainable Development (WBCSD):

> *The circular economy is an economic model that is regenerative by design. The goal is to retain the value of the circulating resources, products, parts and materials by creating a system with innovative business models that allow for long life, optimal (re)use, refurbishment, remanufacturing and recycling.* (WBCSD, 2020)

Whilst earlier attempts to produce maize bioethanol in Brazil had been made, it was FS Fueling Sustainability, starting operations in 2017, that brought consistency and scale to the industry. By 2023, the company was producing two billion litres of bioethanol annually and 1.7 million tonnes of animal feed products across three facilities in Brazil's Central-West region. By combining the expertise of Brazilian and American entrepreneurs, FS Fueling Sustainability successfully adapted the U.S. model—where maize is the primary feedstock for bioethanol—to fit the Brazilian context. The following paragraphs discuss some processes, products and physical flows within this company, with implications for environmental sustainability based on its sustainability report (FS Fueling Sustainability, 2023a).

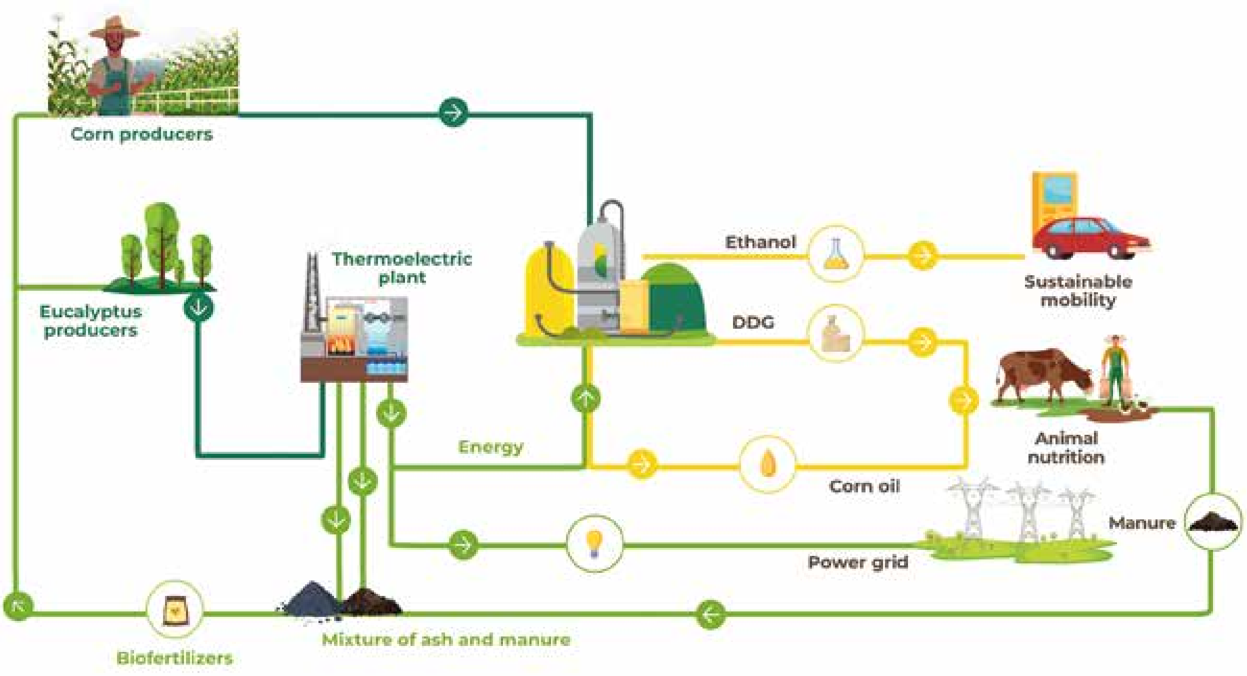
Sustainability in the value chain of the maize ethanol production system is also related to the generation of a range of by-products, which are processed and add value, bringing new products to the market. FS Fueling Sustainability has developed proprietary technology for fibre separation, which separates fibres from ground maize before fermentation, increasing the yield of ethanol production. At the distillery, after fermentation, the remaining solids are concentrated and combined with the previously separated fibres, enabling the manufacture of animal nutrition products with high protein and fibre content. The FS Fueling Sustainability process also enables the extraction of maize oil, a valuable input for animal nutrition and a range of industrial applications.

Due to this integration, maize is fully utilised, enhancing circularity and achieving gains in efficiency and productivity without generating industrial effluents in the processes. Furthermore, FS Fueling Sustainability maintains comprehensive control over the waste generated in its activities, involving the classification of waste according to the applicable technical standards.

Hazardous waste is stored in specific bays with restricted access and containment measures, ensuring safe handling. Non-hazardous waste is sorted into recyclable and non-recyclable categories. Recyclable waste is stored until collected by licensed and approved companies, ensuring proper treatment and minimising environmental impact. These activities are monitored by Brazil's National System of Information on Solid Waste Management (SINIR). SINIR is responsible for issuing monthly waste disposal certificates according to the waste's characteristics and destination. Non-recyclable waste (sanitary waste, food, wood *etc.*) is sent to licensed landfills.

As shown in Figure 56, various circular processes can be identified in the production of maize bioethanol, from agricultural (maize) and forestry (eucalyptus) production towards the final products: bioethanol, food, electricity, as well as nutrient recycling, returning to the soil, where possible, the elements that confer its fertility. A broader, more encompassing and implicit flow in this figure refers to carbon. From atmospheric CO_2, carbon is fixed by solar energy in maize and eucalyptus, processed to produce bioethanol and food, and during final consumption, in the production process and in electricity generation, it is returned to the atmosphere, with limited and indirect fossil energy consumption.

FIGURE 56. Circularity of FS Fueling Sustainability's production system



Source: FS Fueling Sustainability (2023b).

The company also reports having policies and practices aimed at closing the product life cycle, promoting reduction, reuse, recycling and material recovery, as well as minimising waste and using natural resources efficiently. For example, the ashes remaining from the burning of renewable biomass in the boilers, which are one of the main wastes in this agribusiness, are composted and transformed into biofertiliser (FS Fueling Sustainability, 2023a).

During the 2022/2023 harvest, the water-to-ethanol ratio—measuring cubic metres of water used per cubic metre of ethanol produced—decreased by 12% compared to the previous year. This improvement resulted from efforts to optimise water usage and promote more sustainable consumption practices. FS Fueling Sustainability aims to redirect all effluents for fertigation by 2025 and reduce the disposal of waste to landfills by 40% by 2030.

Naturally, circularity in bioethanol production is not exclusive to processes using maize as a raw material. Elevated levels of circularity can also be observed in facilities processing sugarcane, further reinforcing their sustainability (Raízen, 2021). However, it is interesting to note that the significant and somewhat surprising environmental and economic indicators presented by the maize bioethanol production chain as implemented in Brazil (Moreira *et al.*, 2020) are robust and sufficiently motivating to foster a healthy and relevant wave of investment in maize ethanol production capacity, with its remarkable circularity, observed in recent years.

7.

Sustainability in bioethanol production: the Brazilian experience

Making peace with nature is the defining task of the 21st century.

**António Guterres,
Secretary General of the United Nations, 2024.**

The rationale behind bioethanol as an energy vector, in a broad sense, has been systematically studied and assessed over recent decades, particularly in Brazil, where this energy technology has been developed since the early decades of the last century and currently represents one of the key sectors in the national energy matrix.

Indeed, the production of biofuels in general, and bioethanol in particular, is closely linked to the environment, society, agriculture and other economic sectors, justifying comprehensive and detailed evaluations of its impacts and effects. Independent studies have produced a robust and consistent set of sustainability parameters and indicators, covering environmental and socioeconomic aspects, regarding the capacity of this biofuel to meet present needs without compromising the future while respecting the environment and promoting socioeconomic development.

In this chapter, the sustainability of the bioethanol agroindustry is initially presented by highlighting the favourable energy balance of its production process, a key condition for its viability. Environmental aspects are then discussed, especially those related to land use and the effects of agricultural practices. The carbon footprint of bioethanol production chains from sugarcane and maize, as observed in Brazil, is also presented. These topics complement extensive treatments on environmental issues available in BNDES and CGEE (2008) and Bordonal *et al.* (2018). Following this, the socioeconomic impacts on income, employment and regional decentralisation are addressed, complementing the economic assessments developed in Chapter 5. To conclude, the RenovaBio programme is presented, a strategic initiative of the Brazilian government aimed at certifying and economically valuing the decarbonisation achieved through bioethanol within a sustainability framework.

7.1. Energy efficiency in bioethanol production

In any real-world energy processes, involving conversion, storage and transfer of energy in various forms, irreversible energy losses always occur. Strictly speaking, the net useful energy produced will always be less than the total energy consumed. Thus, energy efficiency, defined as the ratio between the final useful energy produced and the total energy consumed, will always be less than one. For instance, to obtain an amount of gasoline equivalent in energy to one barrel of oil, accounting for all upstream and downstream processes, more than one barrel of oil is evidently consumed.

For biofuels, however, there is a notable difference: as solar energy is a freely available resource, all energy inputs—direct or indirect—are considered, except for the solar energy used in photosynthesis, which enables biomass production. In fact, the agro-industrial biofuel production system aims to efficiently process the solar energy captured and stored in plant biomass, using as little external energy as possible and with the highest efficiency. Therefore, the first and most essential condition for the viability and, consequently, sustainability of a biofuel production route is the energy balance of its production process, that is, the ratio between the energy consumed and the useful energy produced during cultivation, processing and final use.

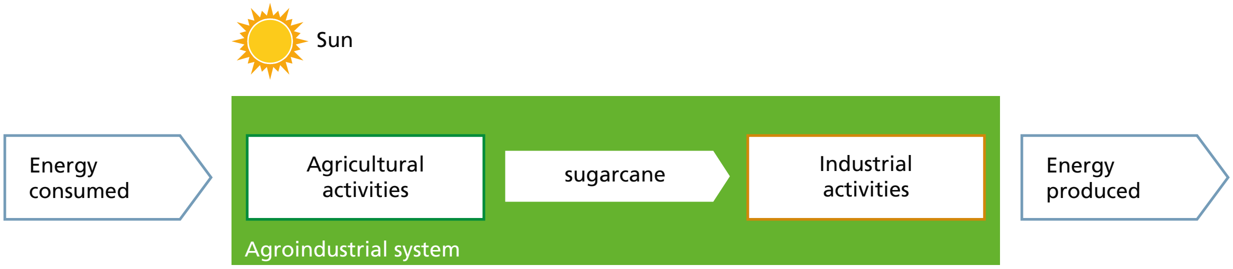
This type of evaluation, especially within energy systems, gained momentum in the 1970s, when rising energy prices prompted the development of efficient and innovative technologies, as well as the systematic measurement of direct (in fuels and electricity) and indirect energy consumption in production processes. Landmark contributions in this field include the books by Boustead and Hancock (1979) on industrial processes and by Pimentel (1980) on agricultural products, which provided methodological foundations and extensive data to estimate the indirect energy consumed in inputs (fertilisers, lime, pesticides, *etc.*) and in agricultural, transport and industrial equipment.

7.1.1. Energy balances in sugarcane bioethanol production

In the same decade that the foundations for energy analysis in production processes were established, Brazil saw a remarkable increase in the use of bioethanol as a transport fuel. At that time, some critics questioned whether more energy might be consumed than produced. This concern was clearly addressed by the pioneering work of Silva *et al.* (1978), who calculated the ratio between energy produced and energy consumed in sugarcane bioethanol production at 5.1. Several subsequent studies yielded comparable results for the energy balance, confirming the energy gain in the agro-industrial process. For example, the Institute for Technological Research (IPT, 1981) and EMBRAPA (Yeganiantz *et al.*,1982) found ratios of 6.7 and 7.7 respectively, for the energy viability indicator of sugarcane bioethanol production. At that time, energy balance studies were also conducted in other contexts and using different raw materials, consistently recognising sugarcane as the most energy-efficient option.

These studies are summarised in Figure 57, where the energy consumed refers to all direct and indirect energy inputs, and it is evident that solar energy is not accounted for.

FIGURE 57. Energy balance scheme for sugarcane bioethanol production



Source: Prepared by the editors.

To confirm previous studies based on sector-wide average parameters, Macedo and Nogueira (1985) conducted a detailed survey of agricultural, transport and industrial processing data from seventy sugar and bioethanol plants in São Paulo State, which at the time accounted for 40% of Brazil's bioethanol production. Results were calculated for the average of the studied mills and for the group of best-performing cases. Energy production included both bioethanol and surplus cogenerated electricity, while energy consumption was assessed in two ways: considering total energy consumed (both fossil and renewable) and considering only direct fossil energy consumption, primarily diesel oil, as shown in Table 16. The latter results, expressed in fuel volumes, indicated that each litre of diesel enabled the production of between 16 and 21 litres of bioethanol.

TABLE 16. Energy balance results for sugarcane bioethanol production at seventy plants in São Paulo State

CASES	ENERGY PRODUCED/ TOTAL ENERGY CONSUMED	ENERGY PRODUCED/ FOSSIL ENERGY CONSUMED
Average values	6.4	8.8
Best cases	9.5	12.3

Source: Adapted from Macedo and Nogueira (1985).

Studies conducted in the years following this work up to the adoption of relevant practices affecting the energy balance did not significantly alter the results for sugarcane bioethanol in Brazil. Macedo *et al.* (2004) evaluated the energy production to total consumption ratio as ranging between 8.3 and 10.2 for average and best cases respectively. Based on this study, where diesel consumption in sugarcane transport stands out, it was inferred that replacing this fossil fuel with biodiesel or ethanol could raise the production/consumption ratio to around 16 (Nogueira, 2010). Using the concepts of "emergy" and embodied energy, applied to agricultural and industrial stages in plants in southeastern Brazil, Pereira and Ortega (2009) concluded that the energy content of the ethanol produced is 8.2 times greater than the fossil energy required for its production.

7.1.2. Energy balances within the scope of life cycle assessment

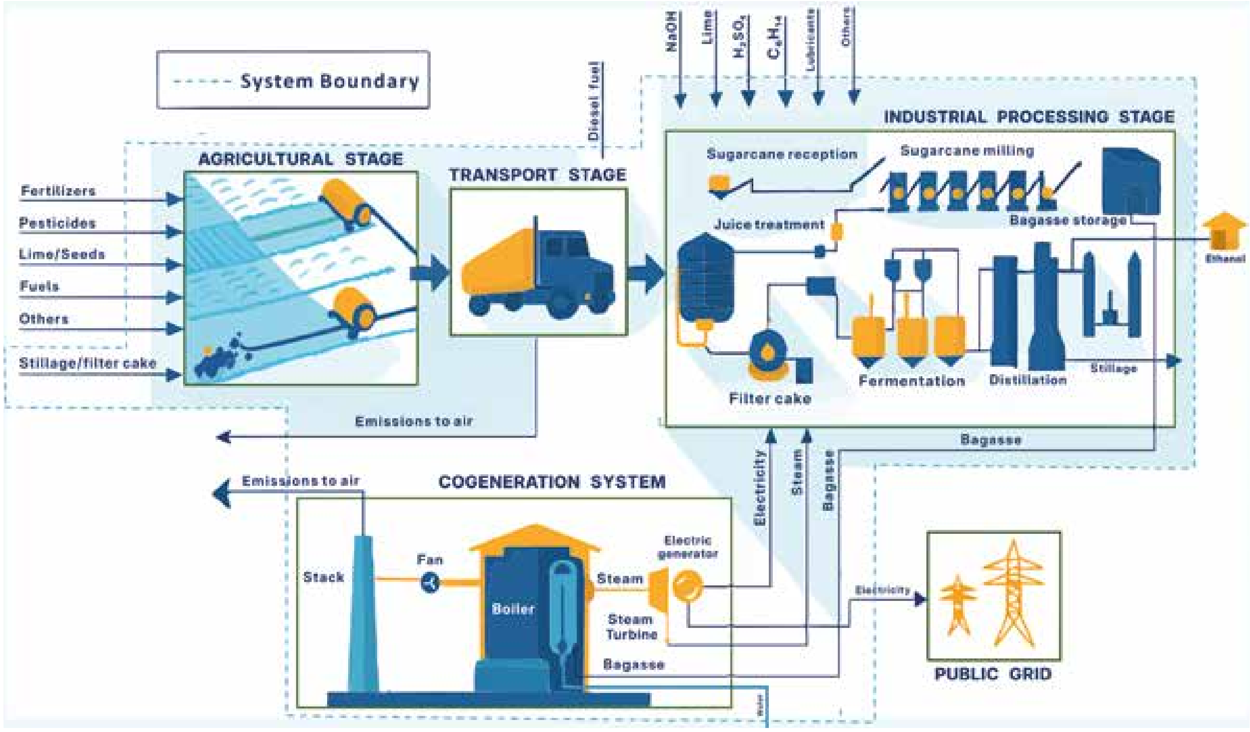
As energy balances assess the direct and indirect consumption of fossil fuels, they enable the determination of emissions resulting from the use of these fuels. With the expansion over recent decades of methodologies and applications of life cycle assessment (LCA) for evaluating greenhouse gas emissions, particularly carbon dioxide, energy balances have been consolidated and are now assessed within this context, through what is known as life cycle energy assessment (LCEA). This adopts the concepts of functional unit, boundaries and common inventories and accounts for energy flows throughout the life cycle of products.

As an LCEA indicator, the ratio of energy output to energy input is maintained, excluding solar radiation as an input. Thus, similarly to the energy balance format from the previous section, the aim is to determine how many units of renewable energy are obtained per unit of fossil energy consumed. The most common formulation, referred to as the net energy ratio (NER), is given by the equation below, which accounts for total energy production, including the biofuel ($E_{Biofuel}$), the excess electricity ($E_{Coproducts}$) and the energy consumed ($E_{Consumed}$) considering both direct energy (fuels and electricity) and indirect energy, associated with the production of inputs, equipment and facilities (Fore *et al.*, 2011).

$$\mathbf{NER} = \frac{E_{Biofuel} + E_{Coproducts}}{E_{Consumed}}$$

In an LCEA applied to biofuel production under Brazilian conditions, Rocha *et al.* (2014) reviewed the methodology, presented the data inventory used and estimated environmental and energy impacts for sugarcane ethanol, the production stages, energy inputs and outputs of which are illustrated in Figure 58. This study used data from Capaz (2009), reflecting values representative of the agroindustry in Brazil's Southeast: sugarcane with a sucrose content (pol) of 14.3% and bagasse (fibre) content of 12.8% and an industrial process based on conservative parameters: yield of 86.5 litres of ethanol per tonne of cane (tc) and a cogeneration system with steam cycles operating at modest pressure levels (2.2 MPa) able to meet the plant's own electricity demand, with some excess generation—11.2% of the bagasse and 15 kWh/tc of electricity.

FIGURE 58. Stages of bioethanol production, energy inputs and outputs and system boundary adopted for determining the NER of the LCEA



Source: Adapted from Rocha *et al.* (2014).

The main data used in the study are presented in Table 17, referring to energy inputs and outputs (kJ/MJ) per unit of bioethanol produced. As one of the most relevant components of energy consumption is fertiliser use, representing over 30% of total energy consumption, two scenarios were analysed: scenario 1 considers the use of chemical fertilisers, while scenario 2 incorporates recycling of filter cake and vinasse—nutrient-rich effluents capable of replacing a significant portion of chemical fertilisers. In scenario 1, 201.0 kg/ha of fertiliser was applied (68.0 kg N/ha, 36.8 kg P_2O_5/ha, 96.2 kg K_2O/ha); in scenario 2, 71.8 kg/ha was applied (50.0 kg N/ha, 8.4 kg P_2O_5/ha, 13.4 kg K_2O/ha) (Capaz, 2009).

TABLE 17. Main data for LCEA evaluation of bioethanol production from sugarcane in mills of Brazil's Centre-South (all values in kJ/$MJ_{ethanol}$)

PARAMETER	SCENARIO 1 WITHOUT BY-PRODUCTS RECYCLE	SCENARIO 2 WITH BY-PRODUCTS RECYCLE
Total energy input	103.33	101.66
Agricultural activities	80.13	78.47
Fertilisers	30.03	18.36
Agrochemicals	10.30	10.30
Diesel	37.28	47.30
Seeds (cane stalks)	2.51	2.50
Transportation	20.28	20.28
Industrial processing	2.92	2.92
Total energy output	1,176.54	1,176.54
Bioethanol	1,000.00	1,000.00
Co-products	176.54	176.54

Source: Prepared by the authors based on Rocha *et al*. (2014).

Summarising the results, Table 18 presents NER values considering the total energy produced, including the excess electricity cogenerated, and considering only the energy content of the bioethanol.

TABLE 18. Net energy ratio estimates for bioethanol production from sugarcane in mills of Brazil's Centre-South

SCENARIOS	INPUT (KJ/$MJ_{BIOETHANOL}$)	OUTPUT (KJ/$MJ_{BIOETHANOL}$)	NER_{TOTAL}	$NER_{BIOETHANOL}$
Without by-products recycle	101.8	1,176.5	11.2	9.8
With by-products recycle	100.4	1,176.5	11.7	9.7

Source: Prepared by the authors based on Rocha *et al*. (2014).

As expected, including excess electricity in the energy output increases the NER by 14 to 20%. Recycling of nutrients, in turn, reduces fertiliser-related energy consumption by 39% despite a higher diesel consumption for field distribution of the effluents. This practice has been increasingly adopted, as presented in Section 6.2: *Use of vinasse and filter cake for the production of biogas and biomethane*.

7.1.3. Comments on energy balances in biofuel production

Despite their simple and straightforward concept—comparing energy inputs and outputs—energy balances can be significantly refined. Beyond detailed assessments and adjustments to the calculation of energy flows, such as regionalising results and incorporating local technical coefficients, more consistent approaches can be adopted for quantifying the energy consumed and produced in biomass processing plants.

As is common in energy studies, energy balances often treat electricity flows and those associated with fuels as if they were equal and directly comparable, although they differ markedly in quality, as thermodynamics explains through the distinction between heat and work. As a result, in energy balances, the desirable expansion of cogeneration—efficiently increasing the supply of surplus electricity—may be misinterpreted as a reduction in energy production since it reduces the availability of bagasse and straw that feed the boilers in cogeneration systems, which inherently suffer energy losses. This issue is increasingly relevant given that modern cogeneration systems in sugarcane mills using bagasse and straw already produce significant energy surpluses, as discussed in Section 6.1: *Bioelectricity in the sugarcane industry*.

The most accurate way of accounting for energy flows of different qualities on a common value basis is through the use of exergy or thermodynamic availability as a weighting factor, translating all energy flows into their potential to perform work. Naturally, exergy analyses and balances require more comprehensive data and greater analytical effort, but their use is beginning to spread. One example is the study by Battle *et al.* (2022), who carried out an energy, exergy, economic and environmental analysis of the integration of sugarcane bioethanol and palm oil biodiesel production in a single biorefinery adapted to Brazilian conditions. Different integration configurations and cogeneration technologies were assessed, with the resulting exergy efficiencies recorded as follows: 25% for low-integration systems, 31% for more integrated systems and 36% for highly integrated systems with gas turbines operating on gasified biomass.

Still within the scope of purely energy-based assessments of biofuel production systems, some studies have applied the energy return on energy investment (EROI) metric, proposed by Hall (2017), to evaluate and compare the energy performance of systems such as power plants and fuel production facilities throughout their lifecycle. In a comparative study of sugarcane ethanol and gasoline as vehicle fuels under Brazilian conditions, from production to end use, Marques *et al.* (2024) found EROI values ranging from 8.20 to 6.52 for ethanol and from 2.34 to 5.50 for gasoline. Their conclusion was that ethanol requires significantly less energy than gasoline to provide the same level of service.

To conclude this review of approaches and results relating to the energy performance of ethanol production systems, it is worth presenting a broad, practical assessment that reveals some useful insights. This involves comparing the energy products of the sugarcane agroindustry with the energy available in the raw material itself. Using typical values for sugarcane cultivation in Brazil—yields of 85 tonnes per hectare, with 14.6% total sugars (sucrose and reducing sugars), 13% fibre and 140 kg of dry tips and leaves—the total available energy is around 7,200 MJ per tonne, equivalent to 1.2 barrels of oil, or 620 GJ of primary energy per hectare, just over 100 barrels of oil per hectare annually. Considering the energy products (secondary energy) per tonne of cane—85 litres of ethanol (1,904 MJ) and surplus electricity of 30 kWh (108 MJ), with no surplus bagasse—the total recovered energy is 2,012 MJ. This means that the agroindustry currently recovers approximately 28% of the energy available in the field. Evaluations of emerging technologies, some of which were outlined in the previous chapter, indicate that this could rise to around 40% (Nogueira & Leal, 2012). There remains, therefore, substantial scope for improving energy efficiency in the ethanol agroindustry.

Energy balances are indeed useful tools for demonstrating the level of energy rationality in the use of biomass as a feedstock for biofuel production. The results discussed above confirm that sugarcane ethanol shows promising energy indicators, supporting its competitiveness and its potential to decarbonise national energy systems, with room for further performance improvements. The breadth and quality of the various studies clearly show that there are efficient routes to producing biofuels, in which the solar energy stored in biomass can be well managed and converted into renewable fuel volumes that far exceed the fossil energy consumed during their production.

7.2. Land use for bioethanol production

This section is based on the technical note prepared for this book by the Agroicone team: Sofia Arantes, Marjorie Guarenghi, Aglaer Cabral, Danilo Garofalo, Luciane Chiodi, and Marcelo Moreira.

The reduction of greenhouse gas (GHG) emissions and the harmony between agricultural production and land use are fundamental to ensuring biofuels effectively contribute to the energy transition. Land use for cultivating energy crops can lead to synergies or trade-offs between GHG emission reductions and other sustainability effects (Cherubin *et al.*, 2021; Vera *et al.*, 2022). It is a dynamic and complex phenomenon shaped by the interaction of market forces, socio-economic needs, public policies and private practices, as well as the biophysical constraints of ecosystems (Moreira *et al.*, 2018). The potential impacts depend on specific contextual conditions, scale of implementation, prior land use, the type of bioenergy crop, soil characteristics, regional climate and agricultural management practices (Cherubin *et al.*, 2021; IPCC, 2019; Vera *et al.*, 2022).

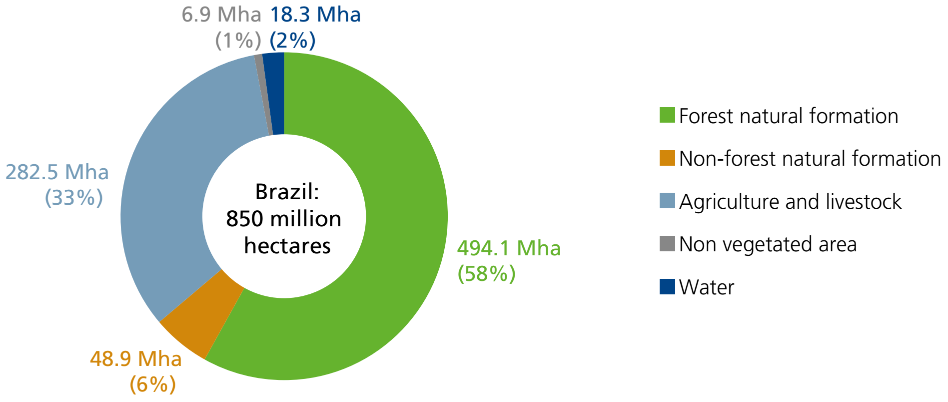
Brazil's strong potential for sustainable bioenergy production reflects both natural conditions and patterns of land use observed in other humid tropical regions. While this topic focuses primarily on Brazil's bioenergy landscape, many of its aspects are equally relevant to promoting sustainable bioenergy in other Latin American, African and Asian countries. These regions have considerable potential for reducing GHG emissions through bioenergy, and the implementation of appropriate policies to encourage investment, overcome costs and ensure competitive prices is essential.

This section presents information on the distribution and management of land use in Brazil, as well as the dynamics of sugarcane and second-crop maize expansion in the country over time. It also highlights good agricultural practices that have been adopted and contribute to the production of low-carbon bioenergy.

7.2.1. Land use and management in Brazilian agriculture

Brazil occupies a privileged position in terms of land use due to its extensive reserves of natural vegetation—home to between 15% and 20% of the planet's biodiversity (UNEP, 2019)—and a dynamic agricultural sector driven by technological development and the availability of arable land (Chaddad, 2015). According to land use data from 2022, around 64% (543 million hectares) of Brazil's territory consists of natural vegetation, mainly forests (58% or 494 million hectares), and 33% is used for agriculture and livestock, with pasture accounting for 58% and cropland for 22%, as shown in Graph 35 (MapBiomas, 2023). Despite more than half of its land being covered by natural vegetation, Brazil is the world's largest exporter of several key agricultural commodities, including soybeans, sugar, maize, coffee, beef and cotton.

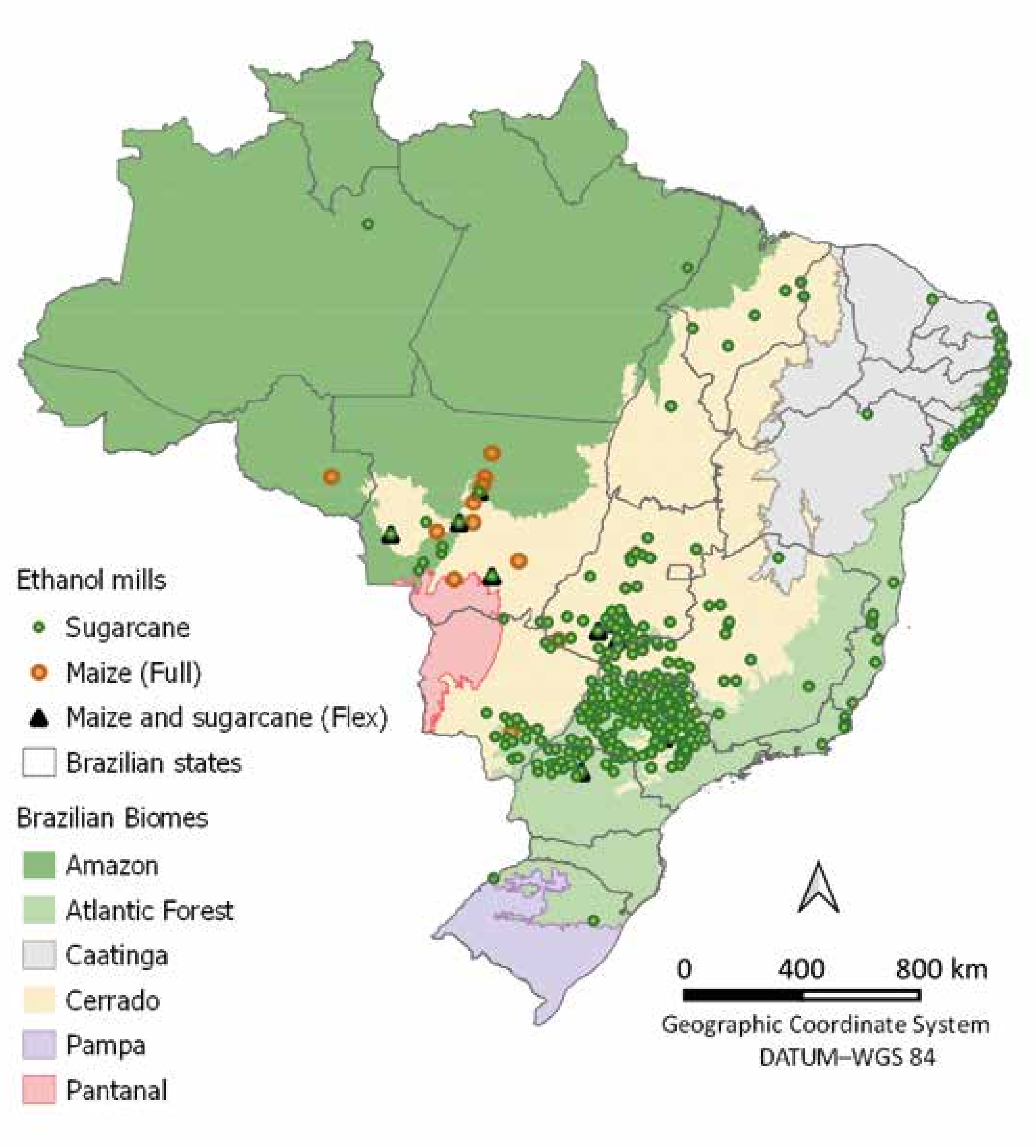
GRAPH 35. Land use and cover in Brazil in 2022



Source: Prepared and provided by Agroicone based on MapBiomas (2023).

The agricultural areas used to produce bioenergy from sugarcane and second-crop maize are concentrated in the Southeast and Central-West regions, predominantly within the Atlantic Forest and Cerrado biomes (MapBiomas, 2023). Sugarcane cultivation occupies less than 1% of the national territory, and second-crop maize used for ethanol production covers around 1.3% (IBGE, 2024). In the 2022/2023 harvest, sugarcane and maize were used to produce approximately 35.6 billion litres of ethanol and 45.6 million tonnes of sugar, in addition to the co-products generated during both processes (ANP, 2023). Figure 59 shows the locations of sugarcane and maize ethanol plants currently in operation in Brazil (EPE Webmap, 2024).

FIGURE 59. Locations of ethanol plants in operation and Brazilian biomes



Note: Brazilian states: Acre (AC), Alagoas (AL), Amapá (AP), Amazonas (AM), Bahia (BA), Ceará (CE), Distrito Federal (DF), Espírito Santo (ES), Goiás (GO), Maranhão (MA), Mato Grosso (MT), Mato Grosso do Sul (MS), Minas Gerais (MG), Pará (PA), Paraíba (PB), Paraná (PR), Pernambuco (PE), Piauí (PI), Rio de Janeiro (RJ), Rio Grande do Norte (RN), Rio Grande do Sul (RS), Rondônia (RO), Roraima (RR), Santa Catarina (SC), São Paulo (SP), Sergipe (SE) and Tocantins (TO).

Source: Prepared and provided by Agroicone based on EPE (2024b).

Managing land allocation is complex and challenging. In Brazil, various public and private laws and strategies are in place to ensure the preservation of natural vegetation and conservation of natural resources. Land use is also addressed through risk management mechanisms that include eligibility criteria and the voluntary adoption of sustainability standards and certification schemes.

The Brazilian Forest Code (Laws 12,651/2012 and 12,727/2012) (BRASIL, 2012) is the country's primary legal instrument for protecting native vegetation. It covers the protection of environmentally sensitive areas (permanent preservation areas – APPs), the sustainable management of forests and the conservation of forest remnants on private land (legal reserve—RL). The Environmental Regularisation Programme (PRA), part of the Forest Code, is a set of measures required from rural landowners to ensure compliance with the law and aims to preserve part of private land for environmental purposes (Freitas et al., 2018). On public lands, Indigenous reserves (FUNAI, 2024), conservation units (Law 9,985/2000) and military lands also contribute to vegetation protection, alongside regional regulations such as the Atlantic Forest Law (Law 11,428/2006).

The National Policy on Climate Change (PNMC) and the implementation of the Action Plans for Preventing and Controlling Deforestation in the Legal Amazon and Cerrado (PPCDAm and PPCerrado) have helped curb illegal deforestation in these biomes. Advances in deforestation alert technologies using remote sensing now enable detailed data collection to monitor and support the enforcement of these policies (BRASIL, 2023c).

In the biofuels sector, Brazil's RenovaBio policy (Law 13,576/2017)—discussed later in this chapter—works in tandem with other land use and environmental protection measures such as the Forest Code to promote more sustainable bioenergy production. RenovaBio aims to reduce GHG emissions in the production, marketing and use of biofuels, and to support the expansion of bioenergy in the national energy mix. The programme encourages the use of already consolidated agricultural areas and excludes feedstocks grown on land deforested after 2018 from eligibility. Rural properties are also monitored through the rural environmental registry (CAR), which records environmental data and property boundaries as part of the Forest Code's monitoring system (ANP, 2018).

Brazil also has the Low-Carbon Agriculture Plan (ABC Plan, 2010-2020 cycle, Law 12,167/2009), which provides rural credit to support low-carbon farming practices and technologies. These include the recovery of degraded pastures, no-till farming and climate adaptation. The new phase, ABC+ (2020–2030), launched in 2021, introduces integrated landscape approaches and offers financing for the recovery of legally protected areas.

In the ethanol sector, other public policies and agreements have also contributed to biodiversity conservation and GHG emission reductions, such as:

- São Paulo State Law 11,241/2002, which introduced the gradual phase-out of sugarcane pre-harvest burning.
- The Green Ethanol Agro-environmental Protocol, signed in 2007 and continued through the Ethanol Plus Green Protocol of 2017, led by the sugar-energy sector in São Paulo to eliminate burning, preserve riparian forests and springs, improve soil conservation and reduce water use in industry, among other measures.
- The Sugarcane Agroecological Zoning (ZAE Cana, Decree 6,961/2009) (BRASIL, 2009), in force between 2009 and 2019, which guided the expansion of sugarcane cultivation by identifying suitable regions and excluding areas of native vegetation, including the Amazon and Pantanal.
- The Soy Moratorium, an agreement by signatory companies not to purchase soy from farms operating on land deforested after July 2008 in the Amazon biome. This has been one of the key measures to prevent deforestation linked to soy production in the Amazon, enhancing traceability and environmental integrity (ABIOVE, 2023). This agreement is crucial to ensuring the sustainability of second-crop maize ethanol, as maize expansion typically occurs on soy-growing land.

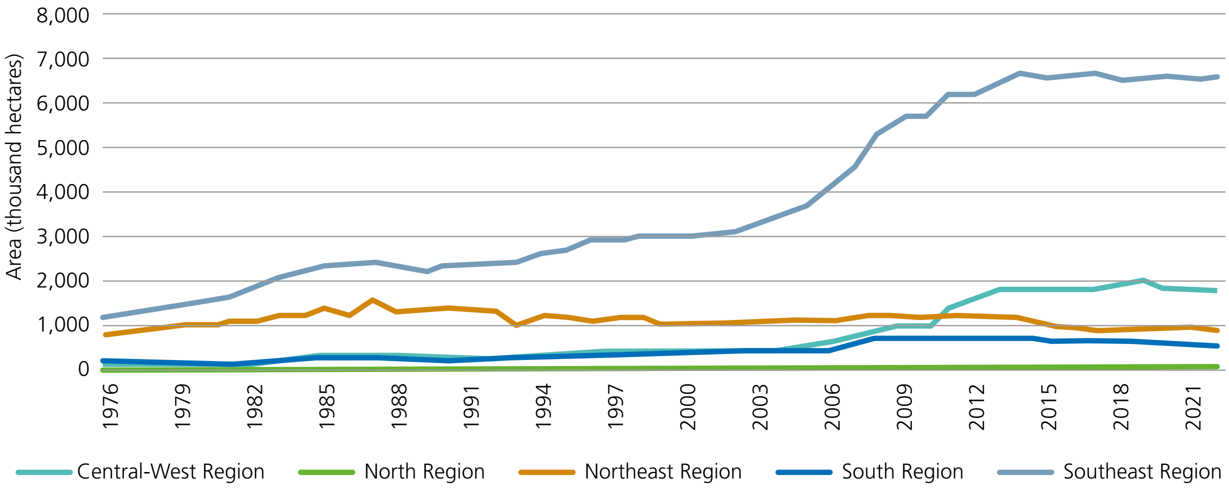
Brazil has made progress in managing the expansion of land used for agriculture and bioenergy. In addition to national policies, environmental laws and private initiatives mentioned above, investments are being made in improving resource efficiency, using agricultural residues, implementing territorial planning and adopting land-saving strategies. These strategies involve technologies that increase sustainable productivity within the same area, reducing the need to convert new land. Examples include no-till farming, integrated crop-livestock-forestry systems, biological nitrogen fixation, the use of bio-inputs in place of non-renewable products and precision agriculture (EMBRAPA, 2021).

7.2.2. Land use and sugarcane expansion dynamics

Sugarcane cultivation in Brazil is predominantly concentrated in the Centre-South and Northeast regions of the country, more than a thousand kilometres from the Amazon. The Centre-South accounts for over 90% of the national sugarcane area and is responsible for around 93% of the country's sugar and ethanol production (ANP, 2024a; IBGE, 2024). In the Northeast, cultivation is limited to coastal areas, mainly in the states of Alagoas, Pernambuco and Paraíba. This region contributes roughly 9% of the national sugarcane area and has experienced a contraction in the crop, with a reduction of approximately 20% in planted area between 2000 and 2023 (IBGE, 2024).

The State of São Paulo accounts for 56% of the country's sugarcane area and is the leading producer of both feedstock and ethanol, concentrating around 170 sugar-energy mills. Other important states in the Southeast include Minas Gerais and Goiás, which account for 10% and 9% of the area, respectively. Since the mid-2000s, production has expanded into states in the Central-West such as Goiás, Mato Grosso do Sul and Mato Grosso, which together now represent 18% of the cultivated area (IBGE, 2024).

GRAPH 36. Evolution of harvested sugarcane area in Brazil, by region



Source: IBGE (2024).

Sugarcane production in Brazil has primarily expanded over degraded pasturelands (Guarenghi *et al.*, 2023; Mapbiomas, 2023). Recent studies based on satellite imagery and land use and land cover mapping indicate that nearly 98% of the expansion over the past two decades occurred on land previously used for agricultural and livestock purposes. An analysis of sugarcane production areas recorded in the rural environmental registry (CAR), covering the Centre-South and North regions, found that 25% of the sugarcane area in 2020 had already been cultivated in 2000. The increase of 6.1 million hectares observed during this period occurred 60% over pasturelands (mainly degraded), 22% over crop-pasture mosaics and 16% over annual crops—especially after 2008 in states such as Goiás and Mato Grosso (Guarenghi *et al.*, 2023; Mapbiomas, 2023).

Sugarcane expansion over native vegetation has fallen considerably in recent decades. Only 1.6% of the current sugarcane area corresponded to native vegetation in 2000 (Guarenghi *et al.*, 2023; Hernandes *et al.*, 2022; Mapbiomas, 2023), and this share declined even further after 2008, reaching just 0.9% (Guarenghi *et al.*, 2023; Mapbiomas, 2023). Sugarcane-producing CARs include approximately 2.3 million hectares of native vegetation (including forest, savannah and wetland formations), which showed only a slight variation of 0.3% between 2000 and 2020. Producers have gradually adopted measures to ensure environmental compliance and meet the requirements of the Forest Code, such as legal reserve deficit compensation and the preservation of native vegetation according to legal provisions (Guarenghi *et al.*, 2023; Cherubin *et al.*, 2021; Hernandes *et al.*, 2022).

Brazil still has significant potential for sustainable sugarcane expansion. It is estimated that the cultivated area will increase from 8.2 million hectares in 2022 to 9.2 million hectares in 2032, assuming an annual productivity gain of 1.4%, with around 56% of this expansion directed towards ethanol production (EPE, 2022). At present, approximately 16 million hectares of pasturelands are considered suitable for sugarcane cultivation, excluding environmentally sensitive areas and considering biophysical constraints (Nogueira *et al.*, 2024). Over half of this potential (9.5 million hectares) corresponds to moderately or severely degraded pastures, mainly in the border regions of the states of Mato Grosso do Sul (4.0 Mha), Goiás (1.8 Mha), Paraná (0.5 Mha) and São Paulo (1.4 Mha). These degraded pasturelands show high productive potential for sugarcane, with most estimates exceeding 85 t/ha, particularly in Mato Grosso do Sul and Goiás (Nogueira *et al.*, 2024).

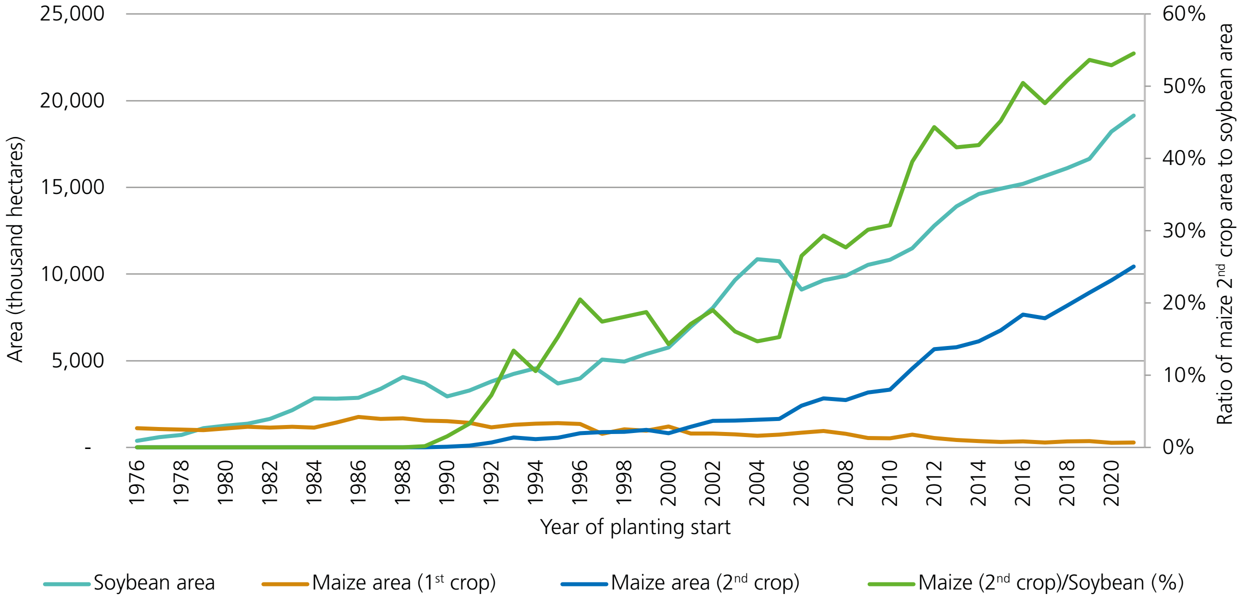
7.2.3. Land use and dynamics of second-crop maize expansion

In Brazil, the production of second-crop maize for ethanol and the respective plants are predominantly concentrated in the Central-West (73%) and South (14%) regions. The State of Mato Grosso alone accounts for 43% of the second-crop maize area, followed by Paraná (14%), Mato Grosso do Sul (13%) and Goiás (10%) (CONAB, 2024a).

Ethanol from maize produced in multicropping systems is an innovation compared with traditional agricultural systems, especially as it does not require additional land for expansion due to its rotation with soybeans in the same cropping year. Studies show that the expansion of second-crop maize has mainly taken place on consolidated soybean areas. According to MapBiomas (2023) and Agrosatélite (2022), 79% of the second-crop maize area in Mato Grosso in 2021 had already been planted with soybeans in 2015, 12.3% with pasture, 5.5% with temporary crops, 2.2% with other land uses and 1.1% with natural vegetation.

Over the past decades, the growth in second-crop maize area has been accompanied by a reduction in first-crop maize area, as shown in Graph 37. Between 2000/2001 and 2022/2023, second-crop maize area in Brazil expanded by approximately 14.7 million hectares (Mha), while first-crop maize area fell by 6 Mha. Over the same period, the soybean area grew from 14 Mha to 44 Mha, an increase of 30 Mha (CONAB, 2024a). In the Central-West, 56% of the soybean area in the 2022/2023 season was also used for second-crop maize, leaving 44% available for the expansion of second-crop maize or other off-season crops.

GRAPH 37. Area of soybeans, maize (first and second crop) and share of second-crop maize on soybean fields in the Central-West region



Source: Prepared and provided by Agroicone based on CONAB (2024a).

Between the 2011/2012 and 2022/2023 seasons, Brazil increased total maize production by 81%, reaching 132 million tonnes in 2022/2023. This growth was driven mainly by the expansion of second-crop maize, which grew from 39 million tonnes in 2011/2012 to 102 million tonnes in 2022/2023, a 162% increase. During this period, the share of second-crop maize in Brazil's total maize production rose from 54% to 77% (CONAB, 2024a).

Gurgel *et al.* (2024) show that realising the production potential of second-crop maize allows DDG, a co-product of maize ethanol, to replace part of the grains used in animal feed (*e.g.*, maize and soybean meal), reducing land requirements for livestock and the risk of land use change. Furthermore, results indicate an additional 148,000 hectares of secondary vegetation in 2030 under the second-crop maize ethanol expansion scenario compared with the baseline, which could reduce the compliance costs associated with Brazil's land use legislation.

According to BRASIL (2023d) projections, the second-crop maize area is expected to grow significantly, reaching 22.2 million hectares by 2032/2033. Over the same period, total maize area in Brazil (including both crops) is projected to reach 25.7 million hectares. Thus, the second crop is expected to represent about 85% of Brazil's total maize area in 2032/2033.

7.2.4. Appropriate agricultural practices for low-carbon biofuel production

The use of appropriate agricultural practices is essential for low-carbon bioenergy production, and Brazil has made progress in this area. Feedstock cultivation is one of the stages with the highest GHG emissions in the biofuel supply chain.

Various agricultural management practices have been adopted to ensure sustainable and efficient ethanol production, such as multicropping, crop rotation, cover cropping, nutrient management planning, use of low-emission fertilisers and reduced soil tillage (IEA, 2024c; Cherubin *et al.*, 2021), as summarised in Figure 60. Precision agriculture has also played a key role, with satellite monitoring systems, moisture sensors and drones being implemented to optimise the use of inputs such as fertilisers and irrigation (EMBRAPA, 2022a; Bolfe, 2024).

FIGURE 60. Example of improvements in agricultural practices

Precision agriculture platforms

- Increased efficiency
- Efficiency in production costs
- Improved environmental sustainability
- Data-driven decision-making
- Selective and targeted application of inputs
- Effective improvement in pest control
- Improved soil quality, resulting from reduced inputs
- Precision fertilisation, with variable fertilisation rate
- Definition of the best machine paths and optimisation of production

Direct Planting

- Soil protection against erosion
- Increased organic matter in the soil
- Improved soil texture
- Increased soil moisture
- Reduced nutrient loss
- Reduced soil temperature range
- Reduced use of inputs

Crop succession and/or intercropping

- Breaking the cycle of pests, diseases and weeds
- Replenishment of organic matter through increased input of agricultural residues (aerial part and roots)
- Improvement of soil structure
- Increased capacity to make available and retain nutrients in the soil
- Promotion of nutrient recycling
- Making the direct planting system viable

Agricultural machinery

- Machines designed to perform agricultural tasks more quickly and efficiently, advancing sowing and harvesting, and reducing the risk of periods of water deficit
- Use of tractors, harvesters, planters and other modern agricultural equipment reduces losses during planting and cultivation
- Less soil compaction

Source: Prepared and provided by Agroicone based on Magalhães et al. (2020); Silva *et al.* (2020); and Nóia Júnior & Sentelhas (2019).

Recent advances in agricultural technology have enabled the widespread adoption of multicropping systems, particularly those combining short-cycle soybeans and second-crop maize. Benefits include higher yields per area, improved soil protection and optimised resource use throughout the production process (Novelli *et al.*, 2023; Magalhães *et al.*, 2020; Milanez *et al.*, 2014).

The soybean-maize system used in Brazil is less input-intensive and has more positive effects on the soil compared with monocultures of the two crops cultivated separately. This combination contributes to soil organic matter formation, facilitates root development, protects against leaching and erosion, balances soil temperature and improves permeability (Narimatsu, 2008). The incorporation of soybean residues with maize straw promotes organic matter decomposition and consequently soil carbon input. Legumes such as soybeans have a low carbon to nitrogen (C/N) ratio, leading to fast decomposition and high mineralisation, releasing nitrogen that benefits subsequent crops. Grasses like maize have a high C/N ratio, decompose more slowly and leave residues that remain longer in the soil (Narimatsu, 2008; Azam *et al.*, 1993; Alamaz *et al.*, 2017; Marcelo *et al.*, 2012).

In both sugarcane and second-crop maize cultivation, farmers have taken a more strategic approach by adopting no-till farming, known as a form of regenerative agriculture (Newton *et al.*, 2020; Khangura *et al.*, 2023). Besides reducing CO_2 emissions, no-till farming improves soil fertility, boosts productivity, controls soil moisture and temperature, protects against erosion and lowers production costs (Magalhães *et al.*, 2020; Corbeels *et al.*, 2016; Bordonal *et al.*, 2018).

No-till systems also significantly reduce the risk of land use change, enabling farmers to produce more food and biofuels on the same land, as seen with the soybean-maize system, without expanding cultivated areas. However, it is worth noting that the effects of no-till farming are reversible. If management practices revert to conventional methods, soil carbon levels are likely to fall again, and previously sequestered carbon would be released as CO_2.

More conservation-oriented practices from planting to harvesting have been implemented and continue to be encouraged for sugarcane, as seen with second-crop maize. These include circular economy initiatives, biodiversity preservation, provision of environmental services and, notably, the fulfilment of both domestic and international GHG reduction commitments (Rossetto *et al.*, 2022).

Efficiency gains have also been seen in sugarcane cultivation, with better use of residues, improved varieties and management of seedling planting. The application of vinasse has increased nutrient cycling and soil moisture, leading to higher cane yields, greater straw production and enhanced soil carbon input (Pinheiro Junior *et al.*, 2024; Cherubin *et al.*, 2021; Rossetto *et al.*, 2018). Vinasse use has been optimised, including the addition of mineral fertilisers to avoid separate field fertilisation. Fertiliser recommendations for sugarcane fields have also been revised to boost productivity and the longevity of ratoons, raising micronutrient levels in the soil (Rossetto *et al.*, 2022). In addition, innovative planting methods using pre-sprouted seedlings, combined with nurseries established in renewal fields and the launch of around eight new varieties per year have also contributed to higher crop yields (Rossetto *et al.*, 2022).

The mechanisation of unburnt cane harvesting, with straw left on the soil surface, has replaced manual harvesting of burnt cane, supporting more sustainable production and improving soil health and carbon sequestration over time. Leaving straw in the field plays a key role in adding carbon to the soil (Carvalho *et al.*, 2017), which can affect soil fertility, cane yield, biological activity, nutrient retention, root growth and more (Cherubin, *et al.*, 2019).

Given the potential to produce second-generation ethanol and electricity from sugarcane straw, excessive removal of straw from fields may lead to soil carbon losses. However, these can be mitigated through good management practices (Pinheiro Junior *et al.*, 2024). Strategies to prevent soil carbon depletion in sugarcane fields include crop rotation, maintaining straw cover, reducing ploughing, adopting minimum tillage and applying filter cake, vinasse and biochar (Pinheiro Junior *et al.*, 2024; Tenelli *et al.*, 2021; Bordonal *et al.*, 2018).

Despite the agronomic and environmental benefits of green harvesting, replacing manual harvesting with machinery and the intense traffic of heavy equipment, especially during harvest, has led to high levels of soil compaction. This presents a challenge to adopting practices that reduce soil carbon losses (Pinheiro Junior *et al.*, 2024; Cherubin *et al.*, 2021). An appropriate management strategy to prevent physical degradation in sugarcane areas has been reduced tillage with fewer soil operations than conventional methods, combined with machine traffic control based on GPS, already incorporated in most agricultural equipment used in the sugarcane sector (Luz *et al.*, 2023; Rossetto *et al.*, 2022). In the case of straw collection, a set of mechanised operations that causes further compaction, whole-straw harvesting systems can help improve soil physical quality (Pinheiro Junior *et al.*, 2024).

Beyond the agricultural practices mentioned, the use of degraded land and livestock intensification play a key role in making large areas available, reducing agricultural pressure on forests and areas that could otherwise be used for food production (GTPS, 2017; Silva *et al.*, 2017; Nepstad *et al.*, 2014).

Brazilian pastures with some level of degradation have been used for agriculture, while some degraded areas are being restored (Guarenghi *et al.*, 2023; Mapbiomas, 2023). Pasture restoration by livestock farmers is hindered by the high cost of chemical fertilisers compared with average beef prices, which means it takes a long time to recover the investment (Bragança *et al.*, 2022). For grain and biofuel producers, however, the cost-benefit ratio of correcting soil fertility and acidity has been advantageous. Crop rotation with pastures is a recommended alternative for improving the use of degraded pastures. Advantages of restoring degraded pastures include improved crop productivity, reduced need to clear new land for food and energy production, increased carbon sequestration, lower use of chemical fertilisers, better erosion control, among other benefits (Bolfe, 2024).

The potential for agricultural expansion into degraded low-productivity pastures is vast across Brazil. Around 28 million hectares of planted pastures are estimated to have intermediate or severe degradation levels but high potential for agricultural use. These areas could expand Brazil's grain production area by approximately 35% based on the total area used in the 2022/2023 season (Bolfe, 2024).

The availability of extensive pasture areas represents a promising scenario for bioenergy expansion in Brazil (Nogueira *et al.*, 2024). Livestock intensification and the use of a small share of pastureland could significantly increase Brazil's biofuel output without compromising land for food production. According to Canabarro *et al.* (2023), using just 3.1% of the current pasture area (of which around 63% is degraded to some degree) would be enough to double Brazil's ethanol production.

7.3. Brazilian ethanol as a low-carbon alternative

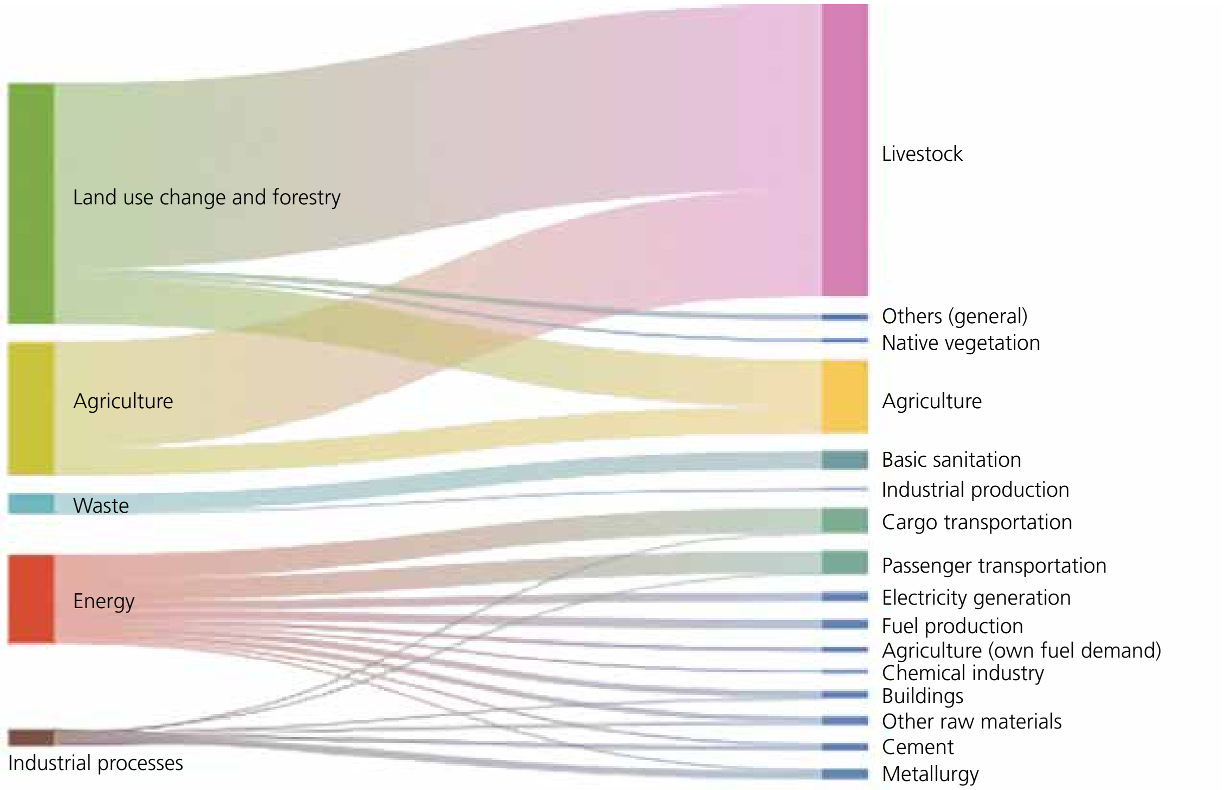
This section is based on the technical note prepared for this book by the Agroicone team: Sofia Arantes, Marjorie Guarenghi, Aglaer Cabral, Danilo Garofalo, Luciane Chiodi and Marcelo Moreira.

The transition to a low-carbon economy is essential for meeting the commitments established under the Paris Agreement, as well as for mitigating the effects of climate change and limiting the rise in global temperatures. The use of bioethanol plays a key role in reducing greenhouse gas (GHG) emissions in Brazil, in supporting the energy transition and in achieving the targets included in the country's nationally determined contribution (NDC).

Under its updated NDC (2023), Brazil has committed to reducing GHG emissions by 48% by 2025 and 53% by 2030 relative to 2005 levels. In addition, Brazil reaffirmed its pledge to reach climate neutrality by 2050 (BRASIL, 2023a). To meet these targets, Brazil aims to increase the share of biofuels and renewable energy in the national energy mix to approximately 18% and 45%, respectively, by 2030 (BRASIL, 2016).

The main sectors contributing to GHG emissions in Brazil are land-use change and forestry, agriculture and livestock and energy (SEEG, 2024). Within the energy sector—the third largest source of GHG emissions in Brazil—the transport of goods and passengers has the highest share, as shown in Figure 61. Biofuels are therefore an essential tool for decarbonising Brazil's transport matrix and mitigating GHG emissions. According to a 2020 survey by the Brazilian Sugarcane and Bioenergy Industry Association (UNICA), the use of ethanol since the introduction of flex-fuel technology in 2003 has avoided 600 million tonnes of CO_2 emissions in Brazil (UNICA, 2020)—an amount equivalent to the total GHG emissions of the country's agricultural sector in 2021 (SEEG, 2024).

FIGURE 61. Contribution of GHG emissions in Brazil, by activity, in 2022



Source: Prepared by the authors based on SEEG (2024).

The following section discusses issues related to land use change—particularly in connection with energy crop cultivation—that can significantly affect carbon footprint estimates of biofuels. It also outlines the main factors that make sugarcane and second-crop maize ethanol produced in Brazil stand out as low-carbon energy alternatives, with lower GHG emissions compared to biofuels made from other feedstocks.

Furthermore, GHG emissions and carbon footprint data for Brazilian ethanol from sugarcane and second-crop maize are presented, comparing them with values for gasoline and ethanol produced in other regions from other feedstocks. Finally, the text explores the potential for Brazilian ethanol to achieve net-zero or even negative carbon footprints when considering improved agricultural practices, refined carbon stock data for land uses, and emerging technologies in Brazil—such as the use of Bioenergy with Carbon Capture and Storage (BECCS)—that may contribute to enhancing the environmental performance of sugarcane and maize ethanol.

7.3.1. Sustainable land use for the promotion of low-carbon bioenergy

Driven by national and international policies and agreements, the expansion of biofuel production has, for more than 15 years, raised questions about potential environmental risks. Concerns have primarily focused on the possible conversion of native vegetation or agricultural land into areas for crops such as sugarcane and/or soybeans, which may negatively impact GHG emissions resulting from land-use change (Alkimim *et al.*, 2015; Berndes *et al.*, 2016; Egeskog *et al.*, 2014; Lapola *et al.*, 2010; Searchinger *et al.*, 2008; Sumfleth *et al.*, 2020).

Land-use change can be categorised as direct (dLUC) or indirect (iLUC), as summarised in Figure 62. dLUC occurs when there is a direct conversion of one land use into another for the production of bioenergy crops (IPCC, 2014)—for example, when pasture, cropland or forest is replaced with sugarcane, maize or soybeans for biofuel production. iLUC, on the other hand, occurs when bioenergy production displaces existing agricultural land use, leading to the conversion of land elsewhere to compensate for the displaced activity (IPCC, 2014). For instance, when farmland is repurposed for biofuel feedstock production, it may push livestock or food production into new areas, potentially causing deforestation. These indirect changes can result from policies or market mechanisms that increase demand for biomass or land.

FIGURE 62. Direct and indirect land-use change in the context of CO_2 emissions

DIRECT LAND USE CHANGE (dLUC):

- Assesses the carbon balance in a given unit of area (*i.e.*, conversion of forest to pasture, sugarcane to annual crops, *etc.*).
- Well-defined area (can be a farm or a hectare).
- Changes in carbon stocks can be measured at the location where the change occurred.
- Use of satellite imagery allows assessing land use before and after.
- Does not allow assessing causality (*i.e.*, crop X that deforested an area was due to the demand for that same crop X or because crop Y removed crop X from its original location and it had to expand, causing deforestation).

INDIRECT LAND USE CHANGE (iLUC):

- Assesses the consequences locally and induced in other places by a given action.
- It is not possible to limit the area of occurrence as its effects are global.
- Much more complete response regarding the consequences of a given action.
- Measurement is difficult, imprecise, and depends on complex hypotheses and models.
- Great difficulty in converging values

Source: Prepared and provided by Agroicone.

Carbon emissions from dLUC can be quantified and are currently required under international biofuel life-cycle analysis protocols (*e.g.* ICAO, 2021). Estimates follow international guidelines, such as those from the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2019), using high-resolution data at the farm or project level or spatially explicit data showing land-use conversions at a given location (Garofalo *et al.*, 2022; Guarenghi *et al.*, 2023).

In contrast to dLUC, GHG emissions from iLUC cannot be directly measured or verified. Indirect effects can only be estimated through modelling—such as global economic equilibrium models used in policies like the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and California's Low Carbon Fuel Standard (LCFS) (IEA, 2024c). However, the values produced by these models vary widely, involve substantial uncertainty and carry risks of arbitrariness (Valin *et al.*, 2015; Woltjer, 2017; Prussi *et al.*, 2021), making iLUC the most contentious aspect in GHG accounting for biofuels (IEA, 2024c).

Experts participating in the Carbon Accounting Workshop held alongside the G20 Energy Transition Working Group in Brazil in 2024 recommended that quantitative iLUC factors should be avoided in GHG accounting due to a lack of evidence that such factors yield consistent results across models or support effective actions to reduce LUC emissions (Biofuture Platform, 2024). Similarly, the International Energy Agency's report *Carbon Accounting for Sustainable Biofuels* suggests that governments adopt qualitative risk-based approaches to address iLUC concerns in the short term while developing global policies to manage its root causes over the long term, including direct land-use regulation and support for sustainable land management practices (IEA, 2024c).

Qualitative risk-based approaches to managing iLUC have already been adopted in some jurisdictions, including the International Maritime Organization (IMO), the European Union's RED III Directive and the Low LUC Risk approach for feedstocks used in sustainable aviation fuel (SAF) under CORSIA (IMO, 2024; EU, 2023; CORSIA, 2022). For example, under CORSIA, the Low LUC Risk approach identifies feedstocks, whose production for SAF is associated with low risk of causing iLUC. In total, two pathways allow feedstock production to qualify as Low LUC Risk (for practices implemented after January 2016—or 2013 in exceptional cases): (i) productivity gains from improved agricultural practices, post-harvest loss reduction, intercropping, sequential cropping or mechanical/non-mechanical enhancements or

(ii) cultivation of feedstocks on unused, marginal or underutilised lands or degraded pastures.

In Brazil, various studies have been developed to improve land-use emissions estimates for Brazilian agricultural products using data ranging from national and state levels (Novaes *et al.*, 2017) to municipal or even property-level scales. These incorporate spatially explicit data, local agricultural practices, refined regional carbon stock parameters and field-based measurements (Garofalo *et al.*, 2022; Guarenghi *et al.*, 2023). Such studies are essential for reducing uncertainty and producing more accurate estimates of the land-use change impacts on GHG emissions from energy crops. Consequently, they allow for more precise carbon footprint assessments of biofuels as region-specific data are preferred over global or national default parameters (IPCC, 2019).

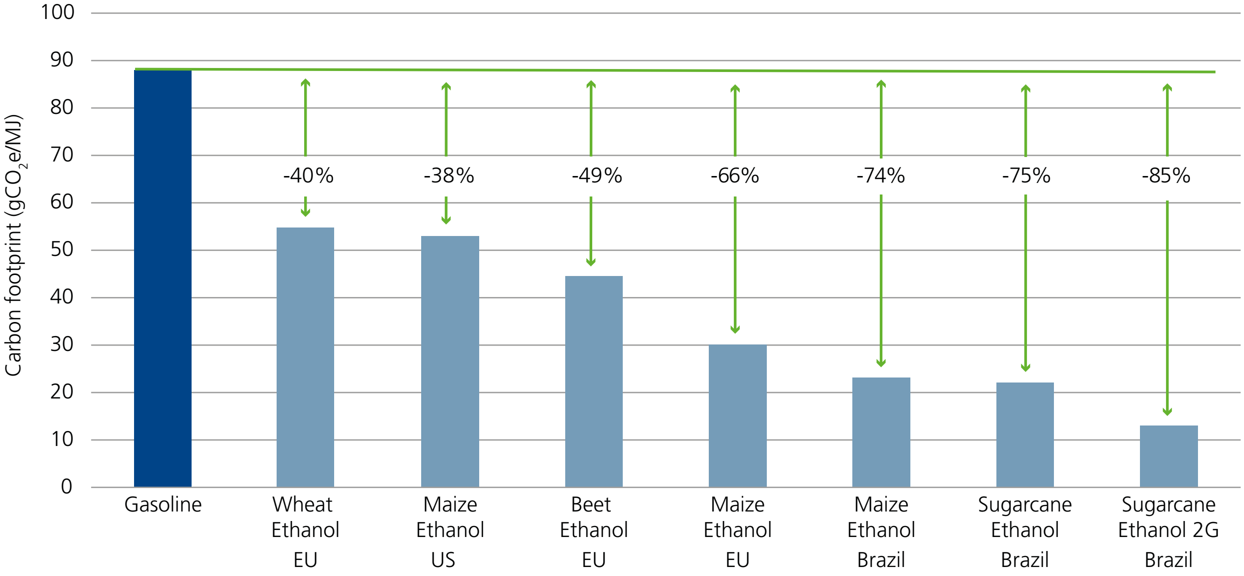
7.3.2. GHG emissions and the carbon footprint of Brazilian sugarcane and maize ethanol

Brazilian sugarcane and second-crop maize ethanol exhibit similar GHG emissions, ranking among the lowest carbon footprints globally when compared to currently available technologies, as shown in Graph 38. Using attributional approaches, which rely on inventorying all input and output flows of system processes as they occur, the typical carbon footprint values of Brazilian sugarcane and second-crop maize ethanol are around 20 to 25 gCO_2e/MJ (ANP, 2024b; Moreira *et al.*, 2020; Pereira *et al.*, 2019). These figures correspond to GHG emission reductions of between 70% and 82% compared to the reference fossil fuel (gasoline = 87.4 gCO_2e/MJ) (ANP, 2024b). Emission reductions may reach 90% under current production conditions (Moreira *et al.*, 2020; Chum *et al.*, 2014, Guarenghi *et al.*, 2023).

The carbon footprints of Brazilian sugarcane and second-crop maize ethanol are also lower than that of maize ethanol produced under conventional (single-crop) systems or other feedstocks such as sugar beet and wheat, grown in temperate climates, as illustrated in Graph 38.

In other methodologies, such as consequential approaches which assess how changes affect the system, the bioelectricity generated during ethanol production must be considered as it replaces grid electricity and avoids emissions from fossil sources. In this case, sugarcane ethanol can achieve emission reductions of over 90% (CARB, 2020) and may outperform other ethanol production routes in terms of carbon footprint.

GRAPH 38. Carbon footprint of gasoline and ethanol produced in different regions from various feedstocks and percentage reduction in GHG emissions from ethanol compared to gasoline



EU: Produced in European Union; US: Produced in United States.

Source: Prepared and provided by Agroicone based on average values from ANP (2024b), Pereira *et al*. (2019), EU (2018), Hamelinck *et al*. (2019), Moreira *et al*. (2020), Manochio *et al*., (2017), and Watanabe *et al*. (2016).

The following paragraphs detail specific aspects of GHG emissions related to sugarcane and second-crop maize ethanol under Brazilian conditions.

a. Sugarcane ethanol

In the case of sugarcane ethanol produced in Brazil, the low carbon footprint values are linked to the nature of the crop, cultivation practices, the areas in which it is grown, land use changes associated with those areas and the use of residues. The following factors contribute to the low emissions of sugarcane bioethanol:

- High energy yield of sugarcane per hectare (between approximately 500 to 600 GJ/ha, considering cogeneration).
- Its classification as a semi-perennial crop, with several harvests from a single planting operation, increasing the capacity for carbon sequestration and storage.

- Sugarcane expansion primarily occurs on already established agricultural land, particularly degraded pastures.
- Soil management techniques adopted in Brazil, such as mechanised harvesting in place of manual harvesting of burnt cane.
- Use of residues such as vinasse for fertigation and straw and bagasse for in-house consumption in cogeneration and energy export, significantly increasing energy generation and boosting energy output from the same planted area.

Greenhouse gas (GHG) emissions in the life cycle analysis of first-generation (1G) sugarcane ethanol are most significant during the agricultural phase due to operations such as the use of machinery and fertiliser application (Cavalett *et al.*, 2013; Nogueira *et al.*, 2022). In the case of second-generation (2G) sugarcane ethanol, produced from harvest residues such as straw, the biofuel's GHG emissions are negligible in the agricultural phase, mainly due to straw being classified as a residue. Most emissions come from the industrial phase, particularly from pre-treatment, enzymatic hydrolysis and the collection and transport of straw from the field to the mill (Prasad *et al.*, 2016; Nogueira *et al.*, 2023).

Technological advances, the adoption of improved agricultural practices and the resulting increase in biomass production will play a key role in mitigating GHG emissions from both 1G and 2G ethanol. In addition, there is mitigation potential through the use of biomethane in place of diesel in agricultural machinery, as well as through greater use of residues such as straw for 2G ethanol production (Nogueira *et al.*, 2023; Junqueira *et al.*, 2017). Expected progress in 2G technology (knowledge, process efficiency, among others) may lead to further mitigation, with carbon footprint values estimated at 7.5 gCO_2e/MJ for 2G ethanol plants (Junqueira *et al.*, 2017).

In terms of land use change effects, the recent literature shows that sugarcane expansion in Brazil poses a low risk of causing deforestation associated with direct land use change (dLUC) (Guarenghi *et al.*, 2023; Canabarro *et al.*, 2023; Hernandes *et al.*, 2022), as well as low risk of indirect and induced effects (dLUC+iLUC) (Follador *et al.*, 2019; Valin *et al.*, 2015; Ferreira Filho & Horridge, 2014; Fiorini *et al.*, 2023; CORSIA, 2022; Woltjer *et al.*, 2017).

The pattern of land use conversion, mainly over degraded pastures, and the replacement of manual harvesting with green cane harvesting contributed to sugarcane produced in Brazil's Centre-South removing, on average, 9.8 million tonnes of CO_2 per year from the atmosphere from 2000 to 2020, totalling 196 $MtCO_2$ over the 20-year period (Guarenghi *et al.*, 2023). When evaluating how land use and land cover transitions affect the net CO_2 balance of the system, the amount removed is even greater, reaching 17 million tonnes of CO_2 per year based on transitions observed in sugarcane production areas registered in Brazil's rural environmental registry (CAR) in 2020. These results are mainly due to the preservation of natural vegetation on rural properties and the increase in natural forest formations. Based on the net carbon removal associated with sugarcane areas over twenty years, the dLUC effect on ethanol's carbon footprint represents a removal of -11.21 gCO_2e/MJ. Given the remaining opportunities for forest restoration in CAR areas, removal gains could be even higher in the future (Guarenghi *et al.* 2023).

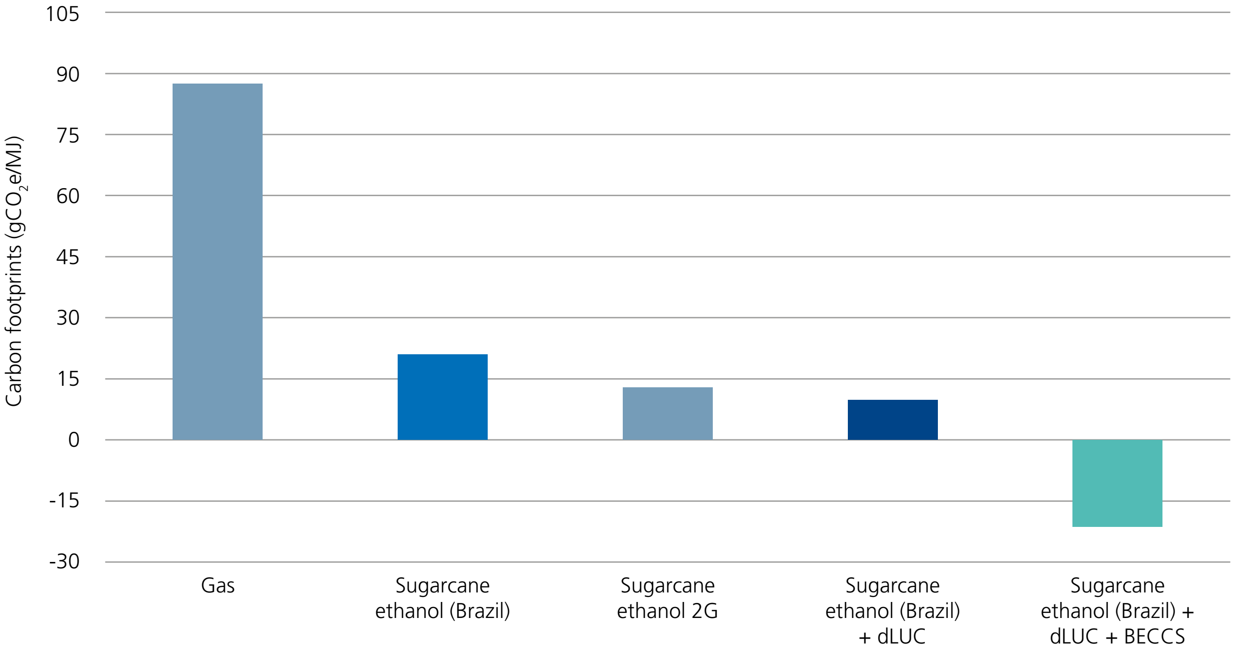
Models evaluating the iLUC impact of both sugarcane ethanol and aviation biofuel derived from sugarcane ethanol suggest lower values than those for other biofuels based on different feedstocks (Follador *et al.*, 2019; Woltjer *et al.*, 2017; Valin *et al.*, 2015). A study by the European Joint Research Centre (JRC) states that the iLUC associated with sugarcane ethanol is negligible (Follador *et al.*, 2019). Under California's Low Carbon Fuel Standard (LCFS), the iLUC value for sugarcane is 11.8 gCO_2e/MJ (CARB, 2019a), which could be lower if estimated using characteristics more representative of sugarcane expansion in Brazil (Guarenghi *et al.* 2023).

For aviation biofuel, CORSIA (2025) attributes an induced effect value of 7.3 gCO_2e/MJ based on simulations using economic equilibrium models such as GLOBIOM and GTAP-BIO. Only pathways based on feedstocks grown at smaller scale, such as carinata, camelina and elephant grass, had lower values than sugarcane-based routes (CORSIA, 2022). Fiorini *et al.* (2023), using a model developed by the Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering of the Federal University of Rio de Janeiro (COPPE-UFRJ) and IPCC scenarios, show that, in general, expansion of sugarcane-based biojet fuel results in negative induced land use change effects in nearly all simulated cases (with or without deforestation controls by the government). In the worst-case scenario for sugarcane, the maximum estimated effect was 5 gCO_2e/MJ.

With the Future Fuel Programme Act (Law 14,993/24) (BRASIL, 2024a), enacted in 2024, Brazil foresees regulatory advances in carbon capture and storage activities. This will contribute to mitigating climate change by enabling the storage of CO_2 in deep underground geological formations (BRASIL, 2023b). The use of BECCS through the capture of CO_2 during the fermentation stage of ethanol production could enable a negative carbon footprint, contributing values ranging from -28.8 to -31 gCO_2e/MJ (CARB, 2019b; Chagas *et al.*, 2016).

In addition to the contribution from Brazilian sugarcane dLUC and the use of BECCS (Guarenghi *et al.*, 2023; Moreira *et al.*, 2016), the adoption of better agricultural practices and the harvesting of green cane rather than burnt cane also help to increase soil carbon sequestration, mitigating GHG emissions and improving soil health (Cherubin *et al.*, 2021; Scala *et al.*, 2012). Altogether, these elements make sugarcane ethanol a promising alternative with high GHG mitigation potential, as shown in Graph 39.

GRAPH 39: Estimated carbon footprint of sugarcane ethanol incorporating different mitigation strategies (approximate values)



Source: Prepared and provided by Agroicone, based on ANP (2024b), Guarenghi *et al.* (2023), and Chagas *et al.* (2016).

b. Second-crop maize ethanol

In the case of maize-based bioethanol, the agricultural stage associated with maize cultivation accounts for the main greenhouse gas (GHG) emissions, primarily due to the use of lime-based products and synthetic and organic nitrogen fertilisers. Estimated results for second-crop maize produced in the State of Mato Grosso indicate that emissions from maize cultivation and its transport to the processing facility represent 78% of total ethanol emissions, with potential variation depending on the environmental performance of maize in different farms (Moreira *et al.*, 2020). The remaining GHG emissions derive from the stages of maize processing and ethanol production, as well as the transport and distribution of the ethanol to its final use (Moreira *et al.*, 2020; Arantes, 2023; Neves & Kalaki, 2021).

The carbon footprint of Brazilian maize ethanol differs from that of ethanol produced in traditional systems, particularly due to second-crop production, lower input use and the reliance on biogenic biomass for energy and steam generation during ethanol production.

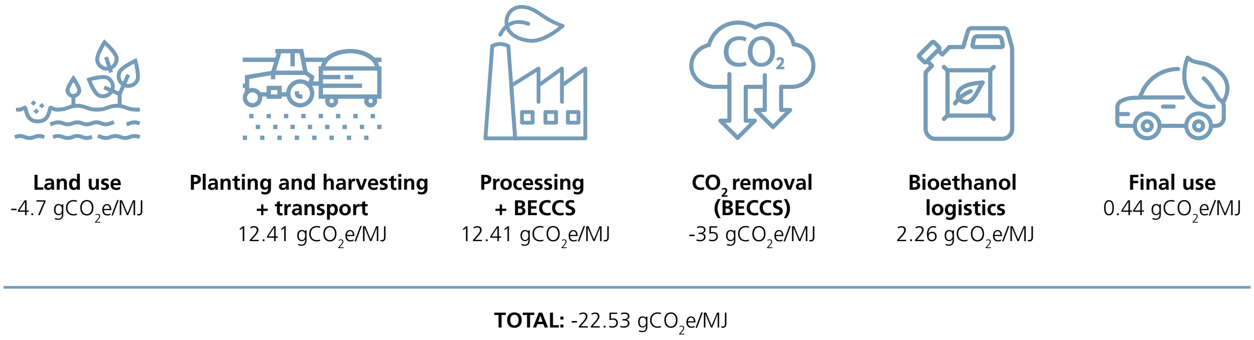
The soy-maize production system enables an increase in output within existing agricultural areas, making the expansion of cultivation for maize unnecessary, as it is planted on already consolidated land. Therefore, there are no direct GHG emissions related to land-use change, which optimises the production cycle and resource use in agricultural production through reduced fertiliser use enabled by the no-tillage system (Vilela *et al.*, 2011; Liu *et al.*, 2019). Moreover, the soy-maize rotation system, incorporating no-tillage practices and maintaining soil cover, contributes significantly to carbon sequestration in the soil over time when compared to conventional systems (without no-tillage), thus mitigating GHG emissions (Scala *et al.*, 2012; Siqueira Neto *et al.*, 2010).

In terms of GHG emissions related to indirect and induced land-use change (iLUC), studies and models estimating values for second-crop maize in Brazil are still limited. However, existing research shows negative or near-zero figures (Moreira *et al.*, 2020; Fiorini *et al.*, 2023). Estimates range from -7.4 to 0.4 gCO_2e/MJ for second-crop maize ethanol (Moreira *et al.*, 2020), and from -298 to 0.4 gCO_2e/MJ for the alcohol-to-jet (ATJ) route of sustainable aviation fuels (SAF) produced from second-crop maize (Fiorini *et al.*, 2023). For aviation biofuel, CORSIA (2025) attributes an iLUC value of 9.3 gCO_2e/MJ for Brazil maize grain ATJ pathways (ethanol and isobutanol).

The negative land-use change values are primarily linked to the existence of second-crop maize, cultivated after the soybean harvest on the same plot and within the same agricultural year. Other factors such as the conversion of pasture to eucalyptus plantations (with higher carbon stocks) and the reduced land requirement for annual crops due to substitution of conventional feed with dried distillers grains (DDG) also help explain the negative land-use change effects (Moreira *et al.*, 2020).

Credits generated from CO_2 capture during fermentation in ethanol production are also a key mitigation strategy for achieving a negative carbon footprint for maize ethanol (Kimura, 2020; CARB, 2019b; Chagas *et al.*, 2016), as shown in Figure 63. A recent well-to-wheel life cycle assessment (LCA) study conducted by UNICAMP (unpublished) estimated that the implementation of bioenergy with carbon capture and storage (BECCS) could reduce the carbon footprint of the biofuel by 35 gCO_2e/MJ. This is consistent with values reported in other studies (Kimura, 2020; CARB, 2019b; Chagas *et al.*, 2016). As such, BECCS could reduce the carbon footprint of Brazilian maize ethanol from 21.2 gCO_2e/MJ (without BECCS, current configuration) to -13.8 gCO_2e/MJ (with BECCS). In the scenario where both BECCS and iLUC are considered, GHG removal reaches 22.5g CO_2e/MJ.

FIGURE 63. Life cycle assessment stages of maize ethanol at one of the main second-crop maize ethanol production units in Brazil*



*Considering maize grown in rotation with soybeans, the use of eucalyptus woodchips complemented by agricultural and agro-industrial residues as energy sources and a production rate of approximately 425 litres of ethanol per tonne of maize processed.

Source: Prepared and provided by Agroicone based on Moreira *et al*. (2020), ANP (2023) and UNICAMP (unpublished study).

In a recent study, Gurgel *et al.* (2024), using a combination of environmental LCA models and computable general equilibrium socioeconomic models (the MIT Emissions Prediction and Policy Analysis—EPPA and the General Equilibrium Project of Analysis of the Brazilian Economy—PAEG), estimated that, under a scenario of 5 billion litres of second-crop maize ethanol produced in Brazil by 2030, GHG emissions could be reduced by between 9.3 million tonnes (without BECCS) and 13.2 million tonnes of CO_2e (with BECCS adoption). The study also identified a land-sparing effect of 160,000 hectares due to livestock intensification. Ongoing studies on the implementation of BECCS are being conducted at the first stratigraphic well in South America, constructed by one of Brazil's largest maize ethanol producers, located in the State of Mato Grosso. The initiative aims to capture and store CO_2 from the fermentation process and has the potential to sequester 423,000 tonnes of CO_2e per year (EPE, 2023), with the capacity to continue storage for around 50 years and a total storage potential of 22 million tonnes of CO_2. The engineering project for injection and storage was developed in accordance with guidelines from the California Air Resources Board (CARB) and the Environmental Protection Agency (EPA) Class VI regulations (FS Fuel Sustentability, 2023a).

Within the context of the energy transition and economic decarbonisation, both sugarcane and second-crop maize ethanol produced in Brazil are essential for mitigating GHG emissions in the transport sector, offering a low carbon footprint and reduced land-use change risk compared to other biofuels from alternative feedstocks. Improved cultivation practices, some of which have already been adopted in recent years, along with technologies such as BECCS, may further reduce Brazil's ethanol carbon footprint and contribute meaningfully to GHG mitigation and climate change efforts.

7.4. Socioeconomic impacts of the bioenergy agroindustry

This section was prepared from notes for this book by Professor Marcelo P. da Cunha from the Institute of Economics at the University of Campinas (UNICAMP), and by Dr Terezinha F. Cardoso, a researcher on bioenergy topics at the same university.

In addition to being regarded as one of the energy alternatives capable of contributing to the reduction of greenhouse gas (GHG) emissions, the adoption of biofuels, when replacing fossil energy sources under appropriate conditions, can have a positive impact on both economic and social dimensions, supporting sustainable development.

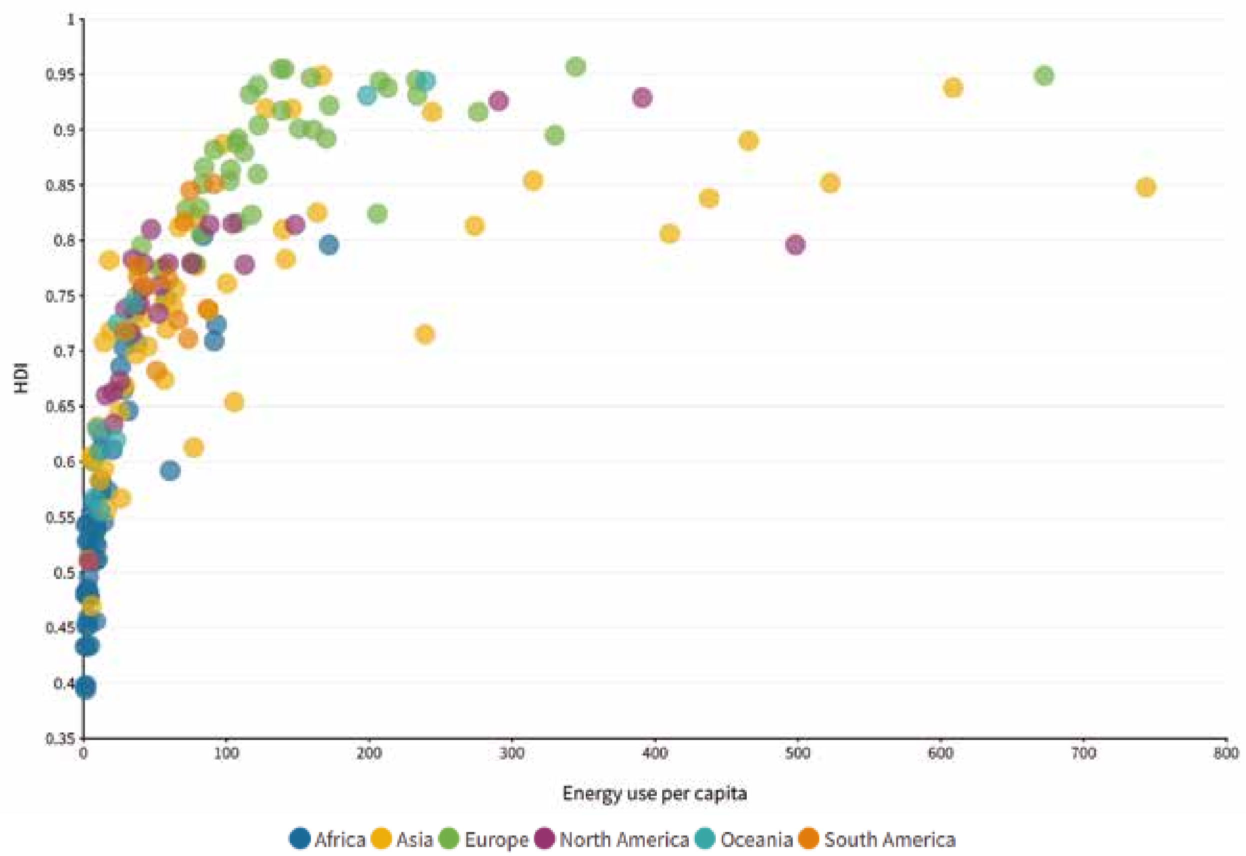
Following a brief overview of the link between the energy transition and sustainable development, this section explores several key aspects of the subject. It presents and compares socioeconomic indicators associated with biofuels and fossil fuels in Brazil, discusses the impact of mechanisation on working conditions and considers the role of biofuels in regional development and their effect on food production.

7.4.1. The energy transition and sustainable development

Access to energy is essential for social and economic development, enabling agricultural, industrial and service sectors to flourish and driving job creation and income generation. Some social indicators are closely linked to the availability and use of energy, such as life expectancy, infant mortality and illiteracy (Kunz *et al.*, 2018). Even though shifts in the economic structures of the world's more developed nations have led to reductions in their per capita energy use (mainly due to the outsourcing of energy-intensive industrial production to other countries in recent decades), the human development index (HDI)—which considers (i) life expectancy at birth, (ii) education levels and (iii) per capita income—still shows a positive correlation with per capita energy consumption, as shown in Graph 40.

The energy transition—the process of shifting from a predominant reliance on fossil fuel-based energy sources to a focus on renewable sources—aims primarily to reduce GHG emissions and thereby mitigate the effects of climate change (BRASIL, 2023b). In addition to environmental sustainability, the energy transition may also enhance energy security by reducing dependence on finite resources located in geopolitically unstable regions (Tasca, 2018). Moreover, the use of biofuels has the potential to drive research and development of modern technologies, create economic opportunities that support regional development and job creation and, by reducing local pollution, improve public health (BRASIL, 2023a).

GRAPH 40. Human development index (HDI) and per capita energy consumption, 2019 (in GJ/year)



Note: The HDI is a 0 to 1 composite index based on indicators for health, education, and income. Circle size represents country population size.
Source: Cleveland (2022).

Therefore, the energy transition must consider the environmental, social and economic dimensions involved to align itself with the sustainable development goals (SDGs)—a global action plan to eradicate extreme poverty and hunger, provide quality education for all, protect the planet and foster peaceful, inclusive societies. Among the SDGs, Goal 7 and its target 7.2—clean and affordable energy—aim to significantly increase the share of renewable energy in the global energy mix by expanding access to modern, sustainable and affordable energy services for all by 2030. Achieving this target will require collaboration between the private sector and civil society to implement effective policies that lead to investment and technological innovation, promoting a shift towards a more sustainable energy matrix, improving living standards and reducing inequality (United Nations, 2015).

7.4.2. Socioeconomic indicators of biofuels in Brazil

In countries where modern bioenergy production makes up a significant share of domestic energy supply, evidence from various studies shows that these activities tend to have more favourable socioeconomic impacts compared to fossil fuel energy chains—particularly in terms of employment generation, gross domestic product (GDP) impact and income distribution. In this regard, biofuels show more inclusive socioeconomic indicators than fossil fuels.

In Brazil, the bioenergy agroindustry plays a key role in generating jobs and income, both through direct effects—in the production and processing of raw materials (mainly sugarcane, maize and soybeans) for biofuel production—and through indirect effects driven by demand for services and inputs in this sector.

When a job is created in one sector of the economy, other jobs are typically generated indirectly as a result of input requirements along the value chain. For biofuel-producing activities, indirect employment is associated with (i) the effects on the production chains of agricultural inputs and (ii) the transport and service sectors, contributing positively to the economic dynamism of the regions involved.

A classic methodological tool for quantifying the spread of direct and indirect effects along value chains in an economy is Input-Output Analysis. This technique enables the examination of relationships of acquisition and supply of inputs (goods and services) among productive sectors of a country or region within a given period. It is typically used to measure the impact on sectoral production levels, employment, income and other economic variables resulting from changes in final demand or product supply, allowing an understanding of how different productive sectors are interlinked (Guilhoto, 2011; Cunha, 2015). Within this approach, final demand consists of (i) household consumption, (ii) government consumption, (iii) exports, (iv) gross fixed capital formation (GFCF, referring to the production of machinery, equipment and facilities to replace depreciated stock and, if possible, expand it to support future economic growth), and (v) changes in inventories (Guilhoto, 2011).

Using the foundations of Input-Output Analysis (which considers the spread of all direct and indirect effects throughout the value chain of the economic sector in question), Table 19 presents the results of a comparison between (i) biofuel production (bioethanol and biodiesel) and (ii) oil refining (diesel and gasoline) in Brazil in 2021 per thousand tonnes of oil equivalent, revealing several important conclusions.

TABLE 19. Comparison of socioeconomic aspects between the biofuels sector (bioethanol and biodiesel production) and the oil refining sector (diesel and gasoline production) in Brazil, 2021

ITEM	MINERAL DIESEL OIL AND GASOLINE	BIOFUELS	BIOFUELS VS FOSSIL
Jobs per energy produced (jobs/1,000 toe)	10.3	60.1	5.86
Sectoral GDP (thousand BRL/toe)	3.3	5.4	1.62
Monthly gross income per job (thousand BRL/job)	4.8	3.3	0.69
Monthly gross income per energy produced (thousand BRL/1,000 toe)	49.6	199.5	4.02
Share of income in sectoral GDP	17.9%	44.4%	2.49

Source: Prepared by the authors based on the Brazilian Supply and Use Tables, 2021 (IBGE, 2023).

Even with the high level of mechanisation in the cultivation of sugarcane, maize and soybeans in Brazil, biofuel production generates 5.86 times more jobs per unit of energy output compared with oil refining. For an energy transition that must also address job and income creation in tropical countries with edaphoclimatic potential for modern bioenergy production, this characteristic is highly relevant for policy formulation aimed at promoting this industry as an inclusive driver of sustainable economic development. It is also noteworthy that the energy output of biofuels has an impact on sectoral GDP that is 62% higher than that of fossil fuel production (mineral diesel and petrol).

Average monthly wages and gross income per job in biofuel production—a sector that includes a significant proportion of agricultural biomass workers with generally lower skill requirements—are lower than those in fossil fuel production. However, when these indicators are evaluated per unit of energy produced, biofuels show values four times greater than fossil fuels.

Another key point relates to the functional distribution of income. The biofuel value chain places greater value on labour than capital compared to the fossil fuel chain. In Brazil, 44.4% of the impact on sectoral GDP from biofuels is attributed to labour compensation and mixed gross income (earned by the self-employed where the labour and capital portions cannot be separated), while for fossil fuels this figure is only 17.9%.

These characteristics further underscore the importance of biofuels as an energy transition alternative that prioritises income generation linked to labour while also delivering more jobs.

7.4.3. Working conditions and mechanisation in the agricultural sector

A determining factor in both the quantity and quality of jobs generated along the bioenergy supply chain lies in the intensification of capital use within the agricultural sector. In the production of bioethanol from sugarcane in Brazil, the shift towards mechanised harvesting was driven by (i) economic motivations (cost reduction), (ii) social considerations (eliminating the strenuous conditions associated with manual cane harvesting), and (iii) environmental imperatives (laws, protocols and incentive programmes aimed at eliminating pre-harvest burning), as outlined in Chapter 5: *Evolution of bioethanol production and use in Brazil.*

According to the National Supply Company (CONAB, 2024b), in the 2023/2024 harvest, 92% of Brazil's sugarcane was harvested mechanically, continuing the trend of increasing mechanisation observed over the past few decades. In the Centre-South region, which accounts for more than 90% of national sugarcane production and features relatively flat terrain favourable to machine harvesting, mechanisation now accounts for approximately 99% of total harvesting. This demonstrates a clear intensification of capital input—that is, increased investment in equipment, technology and infrastructure to enhance economic efficiency. While mechanised harvesting tends to demand more highly skilled labour and offers better pay, it also leads to a reduction in the total number of jobs in the sector.

Although the agricultural phase of the bioenergy supply chain creates more jobs overall, especially in manual operations, it tends to demand workers with lower skill levels and offer correspondingly lower wages. Agricultural mechanisation, particularly in the planting and harvesting of sugarcane, reduces the number of direct jobs but offers higher remuneration due to the greater qualifications required. Furthermore, mechanisation has the potential to generate indirect employment through the manufacture and maintenance of machinery, as well as through the commercialisation of inputs (Machado *et al.*, 2017; Cardoso *et al.*, 2018; Souza, A. *et al.*, 2021).

The economic efficiency promoted by mechanisation—producing more with the same amount of resources, such as energy and labour—can benefit society as a whole since workers displaced from one activity may be redeployed to other roles in different sectors of the economy provided they possess the necessary skills (Walter *et al.*, 2013). However, workers with lower levels of education, particularly those previously employed in manual agricultural tasks such as cane cutting, often face difficulties in finding new roles either within the sugar-energy sector or the broader economy due to a lack of requisite qualifications. It is therefore essential to scale up efforts to support these lower-skilled workers through opportunities for retraining, enabling them to operate machinery or take on roles in other areas of the bioenergy sector or the wider economy.

Social aspects relating to job quality within an economic activity can also be studied using social life cycle assessment (S-LCA), a methodology that allows for the quantification of social variables based on the principles of life cycle assessment (Ugaya *et al.*, 2022). Drawing on this concept, a hybrid methodological approach was developed integrating S-LCA and Input-Output Analysis to assess various social impacts in biorefinery scenarios, focusing on workers as the stakeholder category (Souza, A. *et al.*, 2018).

This approach considered job creation, workplace accidents, salary profiles, levels of education and gender distribution as key indicators within the inventory. When evaluating scenarios with varying levels of agricultural and industrial technology, those with lower levels of technology were found to generate more employment, especially in the agricultural phase. Conversely, scenarios that were more reliant on manufacturing, trade and service sectors exhibited lower workplace accident rates, higher average wages, greater educational attainment and a higher proportion of women in the workforce (Souza, S. P. *et al.*, 2018; Souza, A. *et al.*, 2021).

7.4.4. Biofuels as a driver of regional development

The relevant literature presents numerous studies highlighting the positive impacts of the expansion of the sugar-energy, maize ethanol and biodiesel sectors in Brazil, particularly in terms of employment generation, income and municipal public revenues. These impacts are associated with a significant increase in agro-industrial units and land area dedicated to the cultivation of sugarcane, multicropping maize and oilseeds, often replacing traditional crops and livestock or, in the case of maize, in rotation with soybeans (Martinez *et al.*, 2013; Brinkman *et al.*, 2018; Gonçalves *et al.*, 2021; Cavalcante Filho *et al.*, 2023; Brito *et al.*, 2023; Gurgel *et al.*, 2024).

Sugarcane production for the sugar-energy sector plays an essential role in the economies of small towns where it is established, generating the majority of local jobs and offering average wages that are favourable compared to other agricultural sectors. However, these benefits have been shown to disappear rapidly where sugarcane processing units have been shut down. The resulting dependency of small municipalities on the sugar-energy sector is a concern that warrants careful consideration, particularly in disruption scenarios where appropriate solutions must be found (Defante *et al.*, 2020).

The biofuel value chain includes all agricultural activities related to the production of raw materials, transport to processing units, and distribution to the final consumer. In addition to the direct jobs generated by the sector, there is significant potential for indirect job creation—linked to the demand for inputs and services from other sectors of the economy—as well as induced employment resulting from increased consumption of goods and services within local and regional economies due to the income derived from direct and indirect employment (Martinez *et al.*, 2013).

Beyond job creation, the development of the biofuel supply chain contributes to strengthening regional infrastructure, diversifying the local economy, promoting the construction and/or maintenance of roads to facilitate logistics and encouraging investment in research and professional training (Cortez *et al.*, 2009). It is also worth noting that social indicators—such as life expectancy, infant mortality and literacy rates—are strongly linked to access to energy and rising income levels. These are fundamental factors in enabling local development and the establishment of other industrial and service sectors in the region.

Although much attention is paid to the environmental impacts of expanding bioenergy, the implications for human development are equally significant. This raises important policy questions for the energy and agricultural sectors about how bioenergy can contribute to human development at the municipal level, where more benefits can be reaped, and to what extent local policy structures can be reformed to promote beneficial practices and discourage others (Tomei *et al.*, 2020).

In addition to its direct economic benefits, bioenergy has the potential to improve the HDI of producing regions. As mentioned earlier in this section, the HDI is a valuable tool for assessing the social and economic well-being of a country or region, serving as a key indicator for public policy and sustainable development, and guiding efforts to improve living conditions and reduce inequalities (UNDP, 2024).

In this regard, policies to strengthen and develop rural regions are essential. These should aim to improve the quality of life for rural populations, promote social inclusion, value local culture, reduce inequalities and expand opportunities in rural areas. Strengthening rural economic value chains can also aid reduce rural exoduses (Pedroso *et al.*, 2018).

Brazil's experience in establishing policies to encourage the production and use of bioenergy demonstrates the importance of consolidating partnerships between the public and private sectors. These partnerships can foster progress in less developed regions by supporting investment in more efficient technologies and practices throughout the value chain—including agriculture—thereby reducing disparities in regional development levels (Cunha *et al.*, 2019). In this context, it is vital to understand that sustainable development strategies must encompass job and income generation aimed at eradicating poverty and meeting the current generation's needs, especially those of the population living below the poverty line.

7.4.5. The biofuels market requires balanced taxation

Brazil's extensive experience in the production and use of bioethanol, coupled with improvements in both agricultural and industrial phases and a steep learning curve—especially following the launch of the National Alcohol Programme (Proálcool)—has led to significant cost reductions, making ethanol economically viable without the need for subsidies. Nevertheless, as the energy content of bioethanol is about 70% that of gasoline, a balanced tax treatment based on energy units is required for this biofuel to compete fairly with fossil fuels.

A clear example of this need was observed in Brazil in 2021 and 2022. During this period, nearly all vehicles could run on either gasoline (E27) or bioethanol. However, a disproportionate reduction in federal taxation on gasoline meant that the average consumer price of hydrous ethanol corresponded to 73% of the price of gasoline (EPE, 2024a). As a result, flex-fuel vehicle owners began favouring fossil fuels, leading to increased gasoline imports while demand for bioethanol declined. Therefore, biofuel production must be supported by a regulatory framework that recognises its differential benefits and penalises competitors that profit from negative externalities, which cause harm to both society and the environment.

In this context, Brazil has implemented the National Biofuels Policy (RenovaBio)—the topic of the following section of this chapter—that has been operational since 2019. This policy aims to incentivise biofuel production and consumption, with one of its main tools being the CBIO (carbon credit), a financial asset traded on the stock exchange. Each CBIO represents a certified reduction in greenhouse gas emissions resulting from the substitution of fossil fuels by biofuels. RenovaBio establishes a carbon market whereby biofuel producers and importers can issue and sell CBIOs to fossil fuel distributors with the aim of expanding biofuel supply, decarbonising the energy mix and contributing to Brazil's commitments under the Paris Agreement (Ribeiro & Cunha, 2021).

Beyond its impact on emissions, this policy also helps curb deforestation and fosters job creation and income distribution in Brazil. It also offers market predictability and helps ensure the competitive presence of biofuels within the national energy mix (BRASIL, 2017).

According to simulations presented by Ribeiro and Cunha (2021), RenovaBio has proven effective in promoting decarbonisation by lowering the relative price of ethanol in comparison with gasoline (E27) for end users. The study also shows that CBIO prices are governed by supply and demand: higher CBIO prices tend to occur when conditions are less favourable to biofuels—such as when oil prices are low. Additionally, the more ambitious the GHG reduction targets, requiring greater biofuel participation in the energy mix, the higher the CBIO price is likely to be—assuming oil prices remain constant.

One of the study's conclusions is that RenovaBio may be viewed as a form of environmental insurance. The policy supports the biofuel industry under adverse conditions that might otherwise lead to increased fossil fuel consumption, particularly during periods of steep oil price declines.

7.4.6. Biofuel and food production

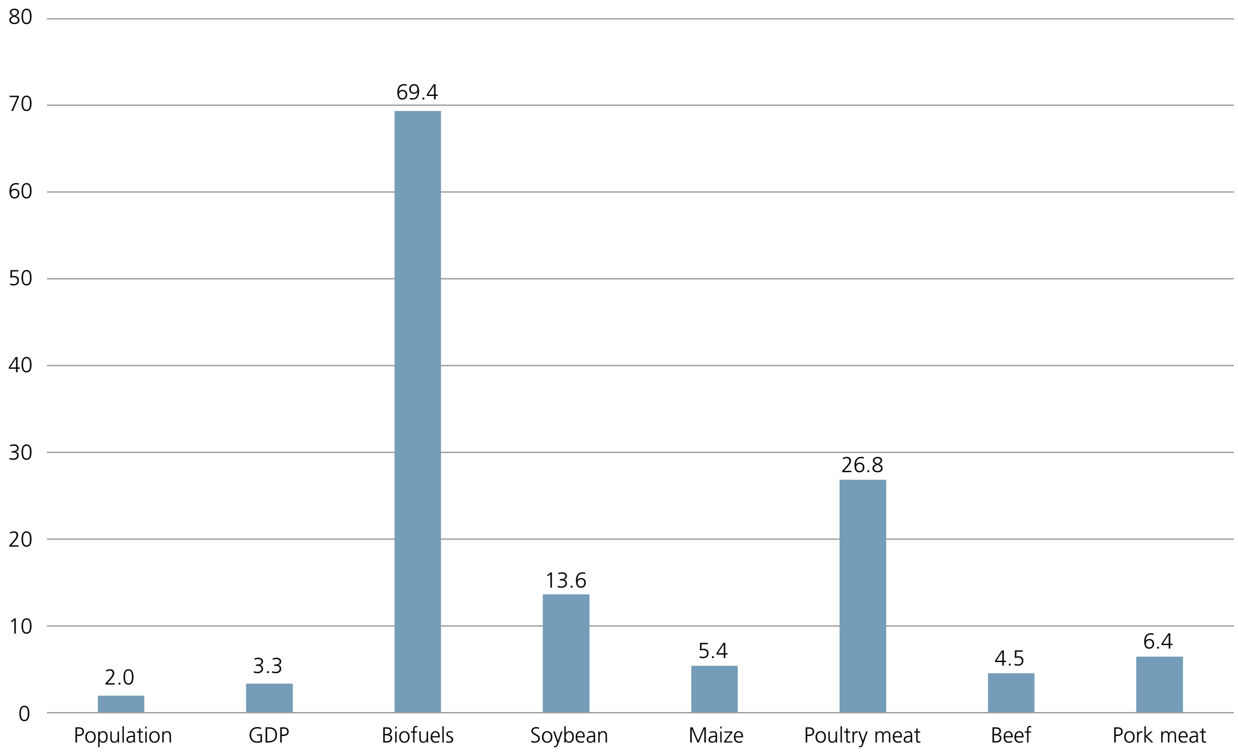
The discussion surrounding the increase in biofuel production alongside food production is one that policymakers must approach with caution.

With its vast territory and rich biodiversity, Brazil stands out as a leading global producer of both bioenergy and food. Its large-scale agricultural capacity and diverse crop base support national food security. Livestock, soy, maize, coffee, sugarcane and tropical fruits all play major roles in Brazil's agricultural economy. Moreover, Brazil is one of the world's top meat exporters, contributing both to global food security and to its own economy (EMBRAPA, 2023; Malafaia & Biscola, 2023).

The growth of Brazil's population, together with the expansion of food and biofuel production over the last five decades, shows that, when supported by appropriate planning and coordinated policies in the energy and agriculture sectors, bioenergy development can coexist with sustainable and synergistic food production.

A concrete example is shown in Graph 41, which presents the growth multipliers for population, gross domestic product (GDP), biofuel production (in energy terms) and agricultural outputs such as soy, maize, beef, poultry and pork from 1975—when the Proálcool programme was launched—to 2021, spanning nearly five decades.

GRAPH 41. Multiplication factors for Brazilian population, GDP and agricultural production from 1975 to 2021



Source: Prepared by the authors based on data from EPE (2023a), FAO (2024), and IBGE (2024).

From 1975 to 2021, Brazil's real GDP increased by a factor of 3.33, while the population grew 1.97 times, leading to a 1.69-fold increase in per capita GDP. Over the same period, biofuel production grew by nearly 70 times, without hindering food production, which grew at a rate exceeding that of both GDP and population. In summary, bioenergy expansion in Brazil has been accompanied by a per capita increase in food production greater than the gains in per capita GDP over the past five decades.

With coordinated actions between the public and private sectors, increased biofuel production can coincide with increased food output. Strategic governmental initiatives such as the Low-Carbon Agriculture Plans (ABC and ABC+) promote sustainable farming practices, aiming to reduce GHG emissions and foster rural sustainable development. These plans respond to global environmental challenges and Brazil's emission reduction commitments under the Paris Agreement (BRASIL, 2023a).

To ensure sustainable solutions that allow biofuel production without compromising food prices or access, integrated systems such as crop-livestock integration (CLI) must be considered. This approach combines agricultural and livestock activities within the same area. Notably, integrating sugarcane and livestock can allow for a significant and sustainable expansion of ethanol (and other biofuels) by using sugarcane bagasse in cattle feed and animal waste as fertiliser and/or biogas in biorefineries (Bonomi, 2018; Volpi *et al.*, 2023; Ferrari *et al.*, 2024). This model supports increased energy production, reduces the land required for meat production, mitigates environmental impact and preserves economic viability (Souza *et al.*, 2021; Dias *et al.*, 2024).

Advanced biofuels also offer a viable alternative for expanding energy supply without affecting food production as they are derived from feedstocks such as agricultural waste (*e.g.*, sugarcane straw and bagasse) and algae grown on non-agricultural land (Klein *et al.*, 2018; Kocak *et al.*, 2022). Second- (2G) and third-generation (3G) biofuels represent a promising solution to the food versus energy dilemma but require ongoing research and supportive policies to unlock their full potential (Bonomi, 2018; Malik *et al.*, 2024).

Improving the food-bioenergy nexus depends on integrated approaches that combine agricultural efficiency, environmental sustainability and social inclusion (FAO, 2022; NatureFinance & FGV-CES, 2024). To that end, key priorities include:

- Investing in research and technology to sustainably raise agricultural productivity.
- Improving logistics infrastructure for the distribution of food and bioenergy.
- Strengthening public policies that encourage responsible farming and rational use of natural resources.

Brazil's experience offers clear evidence that biofuel production can grow alongside per capita food output. Coordinated public and private sector actions, supported by effective policy, productivity gains and sustainability-focused instruments, can lead to a significant rise in both biofuel and food production.

By tackling challenges and embracing emerging opportunities, Brazil can continue to drive the transition towards a greener, more inclusive economy, ensuring food and energy security for future generations, while generating income and employment that support sustainable economic development.

7.5. Environmental sustainability certification in the production and use of biofuels: the RenovaBio programme

This section was prepared from notes for this book by Prof. Joaquim E. Seabra from the Faculty of Mechanical Engineering at University of Campinas (UNICAMP) and Dr. Marília Folegatti-Matsuura, a researcher at Embrapa Environment.

An essential element today to guide and promote the sustainability of biofuel production in Brazil, the RenovaBio programme was launched in December 2016, following a proposal by the Ministry of Mines and Energy, presented by then Director of the Department of Biofuels, Miguel Ivan Lacerda de Oliveira (Oliveira, 2016). At that stage still embryonic, the idea was to develop a government strategy to support the decarbonisation of Brazil's transport sector, focusing on incentivising increased biofuel production within sustainable parameters.

With this purpose, a public policy was structured around three pillars: (1) the establishment of decarbonisation targets for fuel distributors; (2) the accounting of carbon intensity and certification of biofuels, providing the basis for the issuance of decarbonisation credits (CBIOs); and (3) the formalisation of the CBIO market itself as a reward mechanism.

Some of the most important international energy policies of the time were studied, such as the Renewable Energy Directive (RED), Directive 2009/28/EC of the European Community, the vehicle emissions legislation of the California Air Resources Board (CARB), and the Renewable Fuel Standard (RFS), a policy led by the Environmental Protection Agency (EPA) of the United States government.

Although inspired by these policies and their instruments (*e.g.*, the CA-GREET model), RenovaBio and RenovaCalc—its official calculator—have a distinct character: they adopt eligibility criteria as a risk management approach to address land use change (LUC), employ a dedicated calculator capable of expressing the specific environmental profile of biomass and biofuel production at each production facility and use a third-party certification process.

The main methodological features adopted in RenovaBio's carbon accounting are summarised in Chart 4. Its development involved several research institutions, such as the Brazilian Agricultural Research Corporation (EMBRAPA), the National Laboratory for Biorenewables (LNBR, formerly CTBE), the University of Campinas (UNICAMP), and Agroicone, in close coordination with the Ministry of Mines and Energy (MME) and the National Agency for Petroleum, Natural Gas and Biofuels (ANP)—the federal regulatory agency for the fuel sector. The validation of both the method and the calculator involved broad engagement with society, culminating in a public consultation and hearing.

CHART 4. Method and assumptions of the life cycle emissions assessment under RenovaBio

Approach	Attributional life cycle assessment (LCA)*
Scope	"Well-to-wheel"
Functional unit	MJ of fuel consumed
Coproduct treatment	Allocation based on energy content
Waste	List published in Annex I of ANP Resolution 758/2018
Upstream data sources	Background inventories from the ecoinvent database (originally v.3.1), with priority given in the order: Brazil (BR), global (GLO) and Rest of the world (RoW).
Characterisation factors	GWP100, according to AR5 (Stocker, 2013)
Production routes	a) Biodiesel; b) Biomethane; c) Hydroprocessed esters and fatty acids (HEFA) paraffinic synthetic kerosene from soybean; d) Fuel ethanol, broken down into: d1) first-generation sugarcane ethanol (E1GC); d2) first- and second-generation ethanol in an integrated plant (E1G2G); d3) second-generation ethanol (E2G); d4) integrated sugarcane and maize first-generation ethanol (E1GFlex); d5) first-generation maize ethanol (E1GM); d6) imported first-generation maize ethanol (E1GMi).
Calculation tool	RenovaCalc, freely accessible

*Attributional LCA describes potential environmental impacts that may be attributed to a system (*e.g.* the production chain of a biofuel) throughout its life cycle. This approach differs from consequential LCA, which seeks to quantify second-order consequences of a decision.

Source: Prepared by the authors.

With the aim of consolidating it into law, the RenovaBio Project guidelines were approved in July 2017 by Brazil's National Council for Energy Policy (CNPE), the highest body of the federal government in the energy sector. It was then submitted to Congress, where it was approved in December 2017 and sanctioned by the President of the Republic in the same month as the National Biofuels Policy (RenovaBio). The participation of the civil society representative on the CNPE, Plinio Nastari, President of Datagro and a leading expert in the sugar-ethanol sector, was decisive in its passage and in providing essential clarification to public officials and the market.

The following sections present the main concepts of RenovaBio, its development and the key outcomes achieved.

7.5.1. Main concepts of RenovaBio

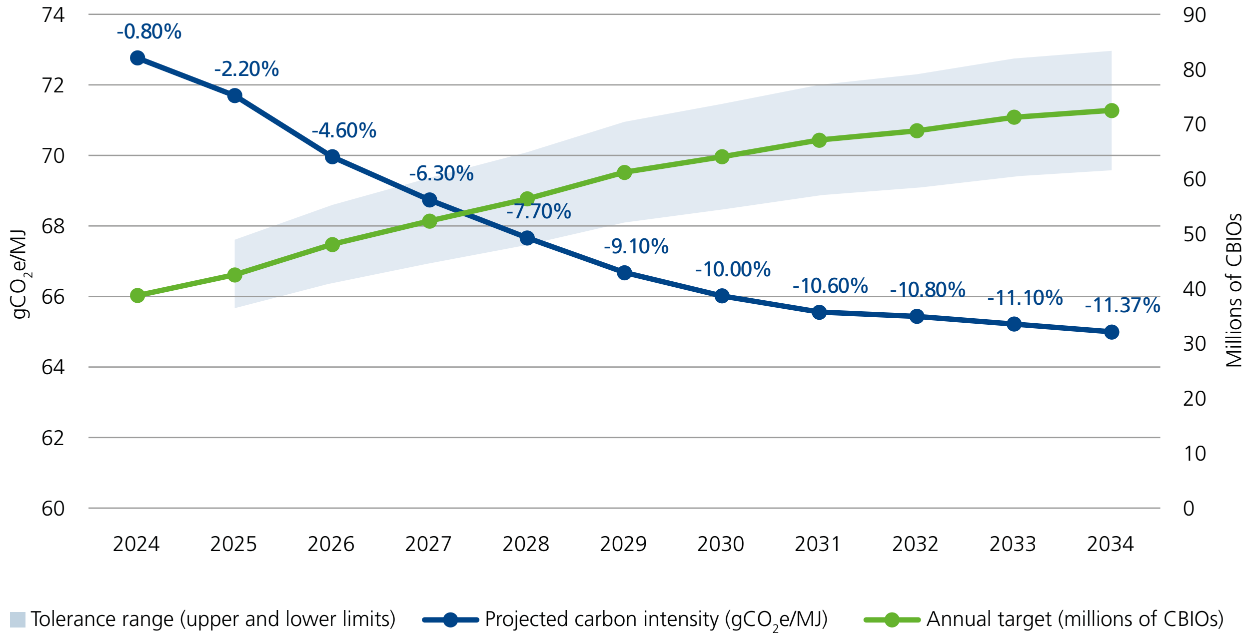
The RenovaBio programme, formally established by Law 13,576/2017, is a national public policy aimed at promoting the decarbonisation of the transport sector in Brazil by encouraging the use of biofuels. It was conceived in response to Brazil's commitments under the Paris Agreement to reduce greenhouse gas (GHG) emissions, and its foundations include:

- Reducing the carbon intensity of the country's fuel mix.
- Stimulating energy and environmental efficiency in biofuel production.
- Strengthening the role of biofuels in Brazil's energy security and environmental sustainability.

The RenovaBio programme is managed by the ANP, which is responsible for regulating the certification of biofuels, setting individual decarbonisation targets and overseeing monitoring and auditing mechanisms. Its three main pillars work in an integrated manner to ensure the programme's effective operation:

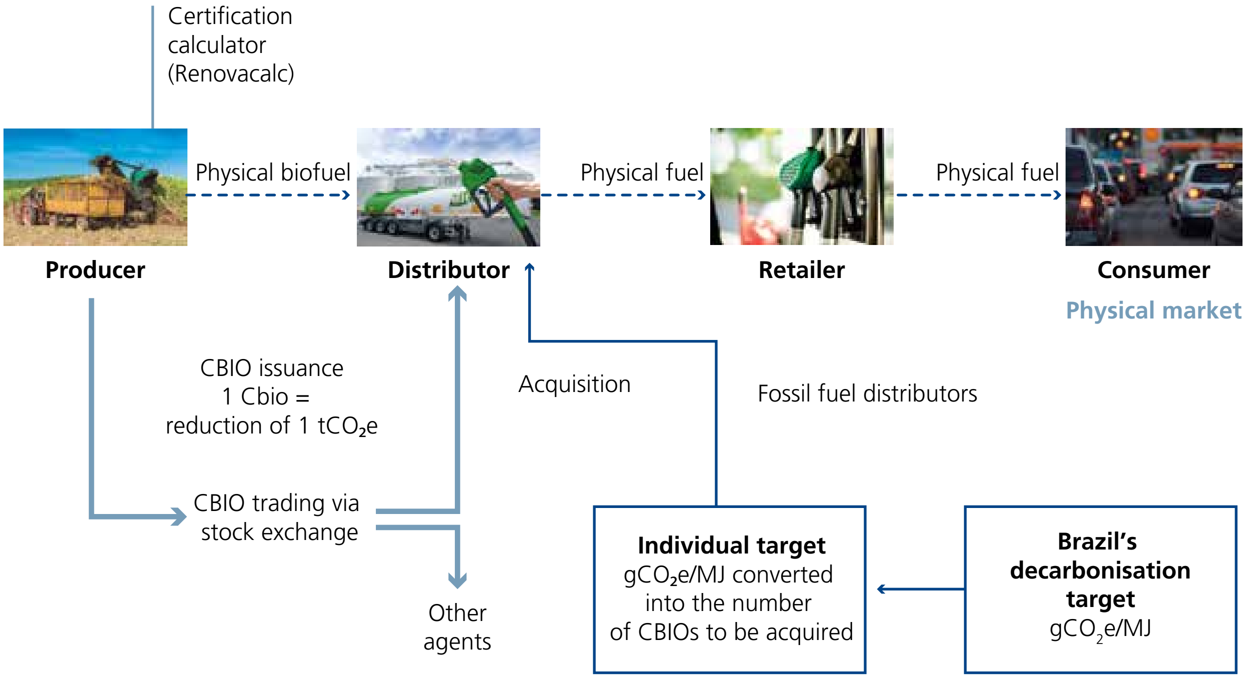
Decarbonisation targets: Set annually by the CNPE, these targets determine the required reduction in carbon intensity in Brazil's fuel matrix, expressed in grams of CO_2 equivalent per megajoule (lower heating value—LHV) of fuel (gCO_2e/MJ). The CNPE defines overall emissions reduction targets for the transport sector considering factors such as economic growth, fuel demand and technological progress. These overall targets are then translated into specific obligations for fossil fuel distributors, proportional to the volume sold in the previous year. According to CNPE Resolution 14/2024, the 2025 targets establish the mitigation of 40.39 million tonnes of CO_2 equivalent, as illustrated in Graph 42. This target reflects a commitment to the continued decarbonisation of the energy mix considering the increased production and consumption of biofuels such as ethanol, biodiesel and biomethane.

GRAPH 42. Mandatory annual GHG emissions reduction targets for fuel commercialisation



Source: Prepared by the authors based on BRASIL (2023d).

FIGURE 64. Operational structure of the RenovaBio programme



Source: Adapted from ANP (2024a).

Decarbonisation credits (CBIOs): These are financial certificates that represent the mitigation of one tonne of CO_2equivalent. They are issued by certified biofuel producers and importers and traded on the stock exchange (B3). Once certified, producers can issue CBIOs in proportion to the energy and environmental efficiency of the eligible volume of their biofuels. These credits are sold to fossil fuel distributors, who use them to meet their decarbonisation targets, as illustrated in Figure 64. CBIOs form the basis of a national carbon market, encouraging emissions pricing and promoting more sustainable practices.

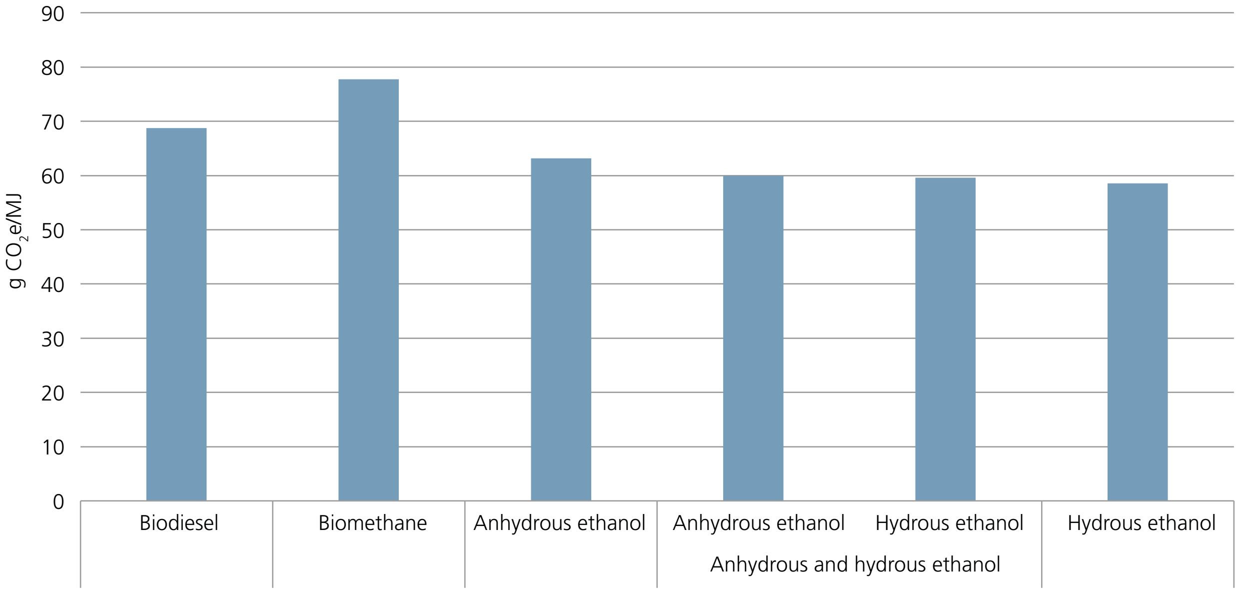
Certification: Environmental certification under RenovaBio is a key element in ensuring the programme's efficiency and transparency. The carbon intensity of a biofuel for a given producer is calculated and the energy-environmental efficiency score (NEEA) is assigned by independent auditors certified by the ANP using RenovaCalc—a spreadsheet-based calculator grounded in life cycle assessment (LCA) of each producer's agro-industrial process. RenovaCalc estimates carbon intensity in gCO_2e/MJ, considering all stages of the biofuel's life cycle (from natural resource extraction to agricultural production, transport, industrial processing and final use) and produces an NEEA by comparing the biofuel with a reference fossil fuel. Graph 43 shows average NEEA scores for certified producers by biofuel and production route (feedstock and process). The higher the score, the greater the environmental efficiency and the higher the CBIO issuance potential.

It is important to note that in order to participate in RenovaBio and be eligible for CBIOs, biofuel producers must meet three land-use related eligibility criteria:

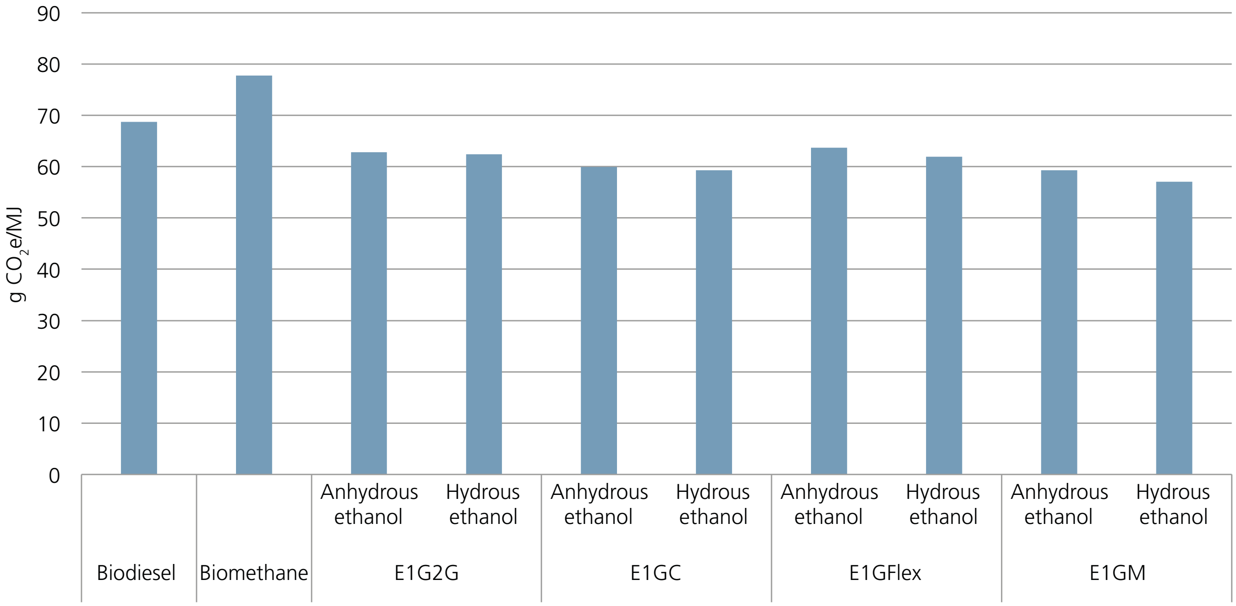
- Certified production must originate from areas with no deforestation after the date of enactment of ANP Resolution 758/2018, 23 November 2018, which regulates RenovaBio.
- The biomass production area must comply with the rural environmental registry (CAR).
- Palm oil production areas must comply with the applicable agroecological zoning regulations.

GRAPH 43. Energy-environmental efficiency scores (NEEA) of biofuels and production pathways, November 2024

GRAPH 43A. NEEA average by biofuel



GRAPH 43B. NEEA average by production pathway



Note: The difference between "hydrous ethanol" and "anhydrous and hydrous ethanol" is due to plants that are certified only for hydrous ethanol or for both. E1G2G: first- and second-generation fuel ethanol produced in an integrated plant; E1GC: first-generation fuel ethanol from sugarcane; E1GFlex: first-generation ethanol from sugarcane and maize in an integrated plant; E1GM: first-generation ethanol from maize.

Source: Prepared by the authors based on ANP (2024b).

The adoption of these criteria and the public disclosure of each producer's results under RenovaBio help to reward processes with recognised emission mitigation potential while offering simpler implementation and lower certification costs. RenovaBio is underpinned by a strong scientific and technical foundation and demonstrates alignment with both national (*e.g.*, Forest Code) and international land-use policies and programmes, ensuring feasibility and uptake by the production sector. RenovaBio effectively applies best practice carbon accounting principles, as recommended by the International Energy Agency (IEA, 2024c).

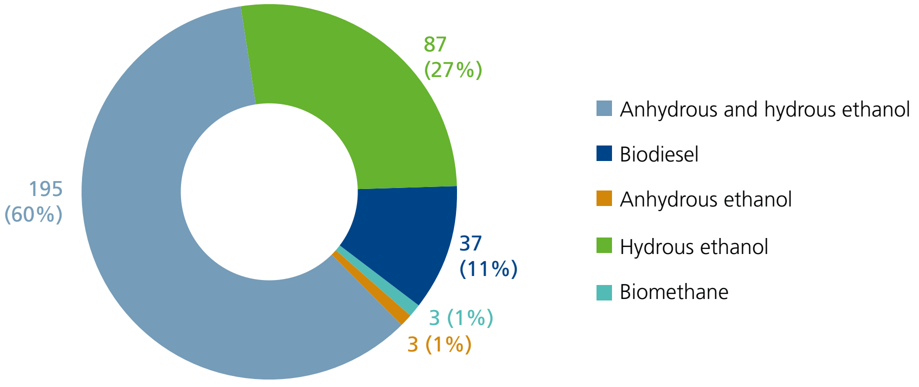
7.5.2. Development of the RenovaBio programme

In 2024, the RenovaBio programme marked five years since the start of its operations. Since 2020, it has contributed to the issuance of over 120 million CBIOs, corresponding to the mitigation of around 120 million tonnes of CO_2equivalent. During this period, the Programme has established itself as a robust and essential public policy for Brazil's energy transition, with the potential to become an international model for decarbonisation.

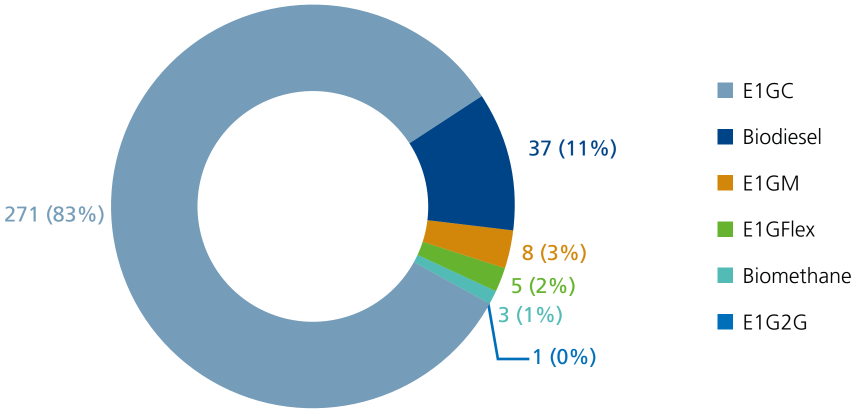
At present, as shown in Graph 44, most of the certificates are linked to first-generation anhydrous and hydrous ethanol produced from sugarcane, with over 70% of production units authorised by the ANP already certified under RenovaBio. Looking ahead, a gradual increase is expected in the participation of biodiesel producers, an expansion in biomethane production and the inclusion of new biofuels.

GRAPH 44. Certified processes under RenovaBio, November 2024

GRAPH 44A. Certified processes by biofuel



GRAPH 44B. Certified processes by production pathway



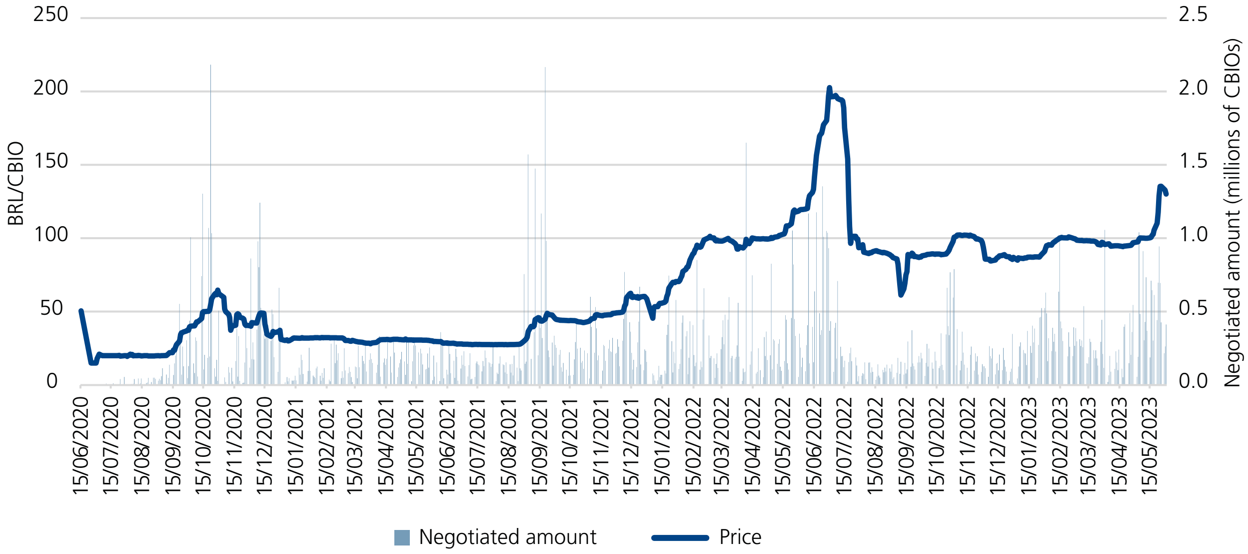
E1GC: First-generation ethanol from sugarcane; E1GM: First-generation ethanol from maize; E1GFlex: First-generation ethanol from sugarcane and maize in an integrated plant; E1G2G: First- and second-generation fuel ethanol produced in an integrated plant.

Source: Prepared by the authors based on ANP (2024b).

Although it has achieved notable progress, the RenovaBio Programme faces challenges that must be addressed to ensure its long-term effectiveness, including cost and structural issues. On the distributors' side, there were frequent complaints about the limited supply and price volatility of CBIOs, as shown in Graph 45. These stakeholders also argued that the burden of decarbonisation targets falls solely on distributors, while other segments such as refining are not subject to similar obligations.

On the feedstock supply side, independent sugarcane producers criticised the investment required for certification, which prevents many small-scale suppliers from participating. Furthermore, there were reports of barriers to their full involvement in the programme as they did not receive a share of the financial gains generated from CBIO trading. However, both issues are expected to be addressed by Law 15,082/2024, which amended the original RenovaBio law to include compensation for independent sugarcane producers through a share of the proceeds from CBIO sales and introduced stricter penalties for fuel distributors that fail to meet their individual targets.

GRAPH 45. Historical series of finalised CBIO transactions on the Stock Exchange (B3)



Source: Prepared by the authors based on B3 (2024).

Among the challenges facing the programme is its integration with other public policies on sustainability and decarbonisation, such as initiatives promoting vehicle efficiency. In addition, maintaining stability in annual targets and regulations is desirable to enhance market confidence. It may also be strategically beneficial for the programme to promote greater fungibility of CBIOs with other carbon certificates.

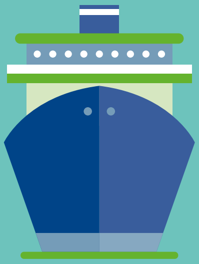
7.5.3. Development of RenovaCalc

RenovaCalc, the spreadsheet used to estimate energy-environmental efficiency scores (NEEA), continues to undergo development. Its improvement is led by the RenovaBio Working Group (EMBRAPA, LNBR, UNICAMP, ANP and MME), supported by research projects. This enhancement process stems from demands within the production sector—such as the inclusion of new biomass types or production routes—from advances in scientific knowledge—such as updates to carbon footprints and GHG emission factors—and from the need to monitor international developments and seek alignment with key initiatives in the biofuels sector, including Carbon Offsetting and Reduction Scheme (CORSIA) by the International Civil Aviation Organization (ICAO) and efforts by the International Maritime Organization (IMO) to decarbonise maritime transport.

ANP Resolution 758/2018 is in the final stages of revision, having undergone new public consultations and hearings in 2023 and 2024, with publication expected in early 2025. The forthcoming updates to RenovaCalc, currently being prepared with documentation made available by the ANP, can be summarised as follows:

1. Update of carbon footprints for agricultural and agro-industrial inputs, adopting version 3.10 of the EcoInvent database.
2. Update of GHG emission factors for agricultural residues (IPCC, 2019).
3. Update of GHG characterisation factors according to Sixth Assessment Report (AR6) (IPCC, 2023).
4. Regionalisation (at the state level) of typical biomass production profiles for sugarcane, maize and soy.
5. Inclusion of new biomass feedstocks for the biodiesel route: palm oil, distilled maize oil and cottonseed oil.
6. Inclusion of a new biomass feedstock for the ethanol route: sorghum.
7. Addition of new co-products in the sugarcane ethanol production route.
8. Creation of new production routes: (a) ethanol from soybean molasses; (b) various routes for sustainable aviation fuel (SAF); (c) co-processed fuel; (d) renewable hydrogen.
9. Proposal of new values for the carbon intensity of benchmark fossil fuels.
10. Estimation of fugitive emissions from biomethane and proposed accounting in its carbon intensity.
11. Solutions to represent negative emissions from BECCS and the use of biochar.
12. New conceptual framework for waste.

These updates aim to more accurately represent production processes and the carbon intensity of RenovaBio biofuels while also diversifying the biomass sources and types of biofuels available, thereby supporting the expansion of the programme.



Part 3

GLOBAL OUTLOOK FOR SUSTAINABLE BIOFUELS

The following chapters present regional and national assessments of the potential for bioethanol production, discuss aspects of the global market for this biofuel, and review the current situation in selected countries. To conclude, recognising that bioethanol can effectively promote an energy transition that is fast, accessible, inclusive, and renewable is summarized in the key messages of this book. Recommendations are offered for overcoming challenges, implementing sustainable biofuel markets, and promoting investment , highlighting the role of international cooperation.

8.

Global perspectives on bioethanol

The real voyage of discovery consists not in seeking new landscapes, but in having new eyes.

Marcel Proust

Bioethanol was one of the earliest fuels used in motor vehicles and was produced in several countries for this purpose during the early decades of the last century, as outlined in Section 2.1: *Brief history of bioethanol as an automotive fuel.* However, particularly due to the growing availability of gasoline at competitive prices, the use of bioethanol for mobility became limited to a handful of countries, where it was retained primarily as a gasoline additive. From the 1990s onwards, interest in this biofuel resurged in many countries owing to its environmental benefits, energy security advantages and contribution to sustainable development. Today, bioethanol is regularly consumed in dozens of countries, as shown in Figure 5, Chapter 2, while many others are currently considering its adoption as a transport fuel.

This chapter begins by introducing the potential for expanding bioenergy production, discussing the conditions that shape this potential and presenting findings from both a global perspective and from studies focused on regions with available agricultural land and suitable edaphoclimatic conditions for ethanol production in Latin America and the Caribbean, Africa, and Asia. An evaluation of Angolan conditions for sugarcane culture expansion is presented as an example of using computational resources and georeferenced databases for establishing potential conditions for bioenergy production at the national level. It then examines the current landscape and future outlook for international bioethanol trade, a subject of growing relevance as consumption expands and production becomes increasingly concentrated in countries with more competitive supply—much like the global oil and petroleum products market. Next, to provide concrete examples of national experiences with bioethanol as a fuel, the chapter presents the current status of ethanol programmes implemented in Latin American countries and comments on the introduction of this biofuel in Guatemala and India, highlighting the challenges and lessons learned. Finally, aspects of ethanol logistics are addressed, presenting the modes of transport currently adopted and their efficiency in moving large volumes of this biofuel.

8.1. Potential for bioethanol production

Several studies have been conducted to shed light on one of the key issues shaping the future of biofuels, and bioethanol in particular: in what quantities, and in which regions, could these energy vectors be made available? In truth, this is a complex issue. The potential supply of biofuels is not a fixed, absolute figure—like a mineral reserve—but rather a dynamic estimate that depends on shifting geographical, economic and political scenarios, as well as on biomass production and conversion technologies, some of which are still under development. As shown in earlier chapters, bioethanol can be produced either from dedicated energy crops, which require arable land, or from agricultural residues, in which case the volume of other goods produced determines its potential.

Moreover—and importantly—the natural resource base for energy crops, such as land and water, is inherently limited and must be shared with food production for humans and animals, industrial raw materials (*e.g.*, textile fibres, pulpwood and others), environmental conservation and other competing uses. This close link with food supply makes the issue even more complex, highlighting the importance of understanding the sustainable potential of biofuel production, conversion and use in the context of food security concerns.

Setting boundaries for biofuel production, especially when incorporating sustainability criteria, is a challenging task. To address this, analytical and computational models have been developed to simulate the stages and impacts of bioenergy production. These models support policymakers in designing bioenergy programmes by evaluating specific contexts and recognising physical limits and energy production priorities. This quantitative approach yields results that must then be assessed in terms of their localised environmental and socio-economic impacts and benefits. The studies on the sustainability of ethanol production in Brazil, presented in the previous chapter, emphasise critical factors such as energy balance and effects on income generation and employment.

In the paragraphs that follow, estimates of bioenergy production potential are first presented from a global perspective, followed by studies that focus more specifically on bioethanol.

8.1.1. Global potential for bioenergy production

Estimates of the global potential for sustainable bioenergy production are typically independent of economic analysis or the existence of consumer markets. Instead, they explore aggregate scenarios of biomass availability, and the technologies required to convert this into final bioenergy vectors. Sustainable biomass supply includes: (a) biomass generated as a by-product of agricultural and agro-industrial activities (*e.g.*, straw, bagasse, sawdust, black liquor); (b) biomass recycled from materials initially produced for other purposes and already used (*e.g.*, part of municipal solid waste); and (c) energy crops (*e.g.*, forestry, sugarcane), factoring in land that is genuinely available for cultivation, excluding land needed for food and fibre production or that is prioritised for other uses or conservation.

From these estimates of sustainable biomass supply—and using technical coefficients for biomass conversion into biofuels and bioelectricity—it becomes possible to infer aggregate potentials for sustainable bioenergy production. These estimates rely on detailed current and prospective data and are shaped by different scenarios for biomass yields and conversion efficiencies.

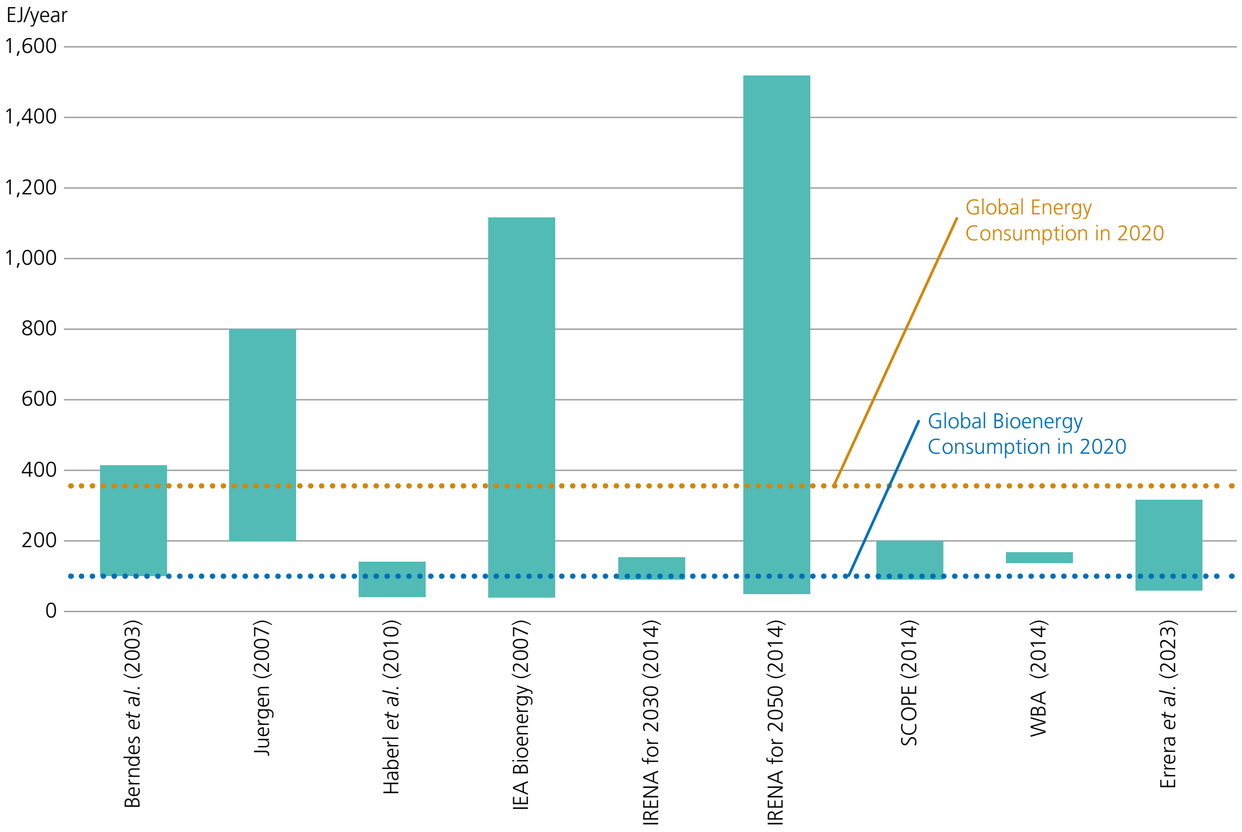
Using this approach, various studies have been conducted for both present conditions and future scenarios. The wide range of results reflects the diversity of options and the inherent uncertainties in land availability, productivity levels, and future biomass supply from forestry and residues. Some studies express potential in terms of primary energy, using biomass as the raw material, while others consider final-use bioenergy production. With that in mind, it is useful to examine some global bioenergy potential estimates.

In both conservative and optimistic scenarios, Berndes *et al.* (2003) concluded that biomass could contribute between 100 and 400 EJ per year to the global energy supply. Juergens (2007) estimated a range of 205 to 790 EJ/year. Bringing together several studies, IEA Bioenergy (IEA, 2007) suggested a range from 40 to 1100 EJ/year, with lower figures assuming the use of only biomass residues, and the higher end assuming intensive agriculture on high-quality land. Emphasising the importance of food production, agricultural technology and natural resource conservation, Haberl and co-authors (2010) projected a more modest potential from 44 to 133 EJ/year by 2050.

The International Renewable Energy Agency (IRENA) estimated bioenergy production potentials ranging from 97 to 147 EJ/year for 2030, and from 50 to 1500 EJ/year by 2050 (IRENA, 2014). In projections for 2035, the World Bioenergy Association (WBA) estimated this potential to be from 134 to 166 EJ/year (WBA, 2016). A comprehensive study by the Scientific Committee on Problems of the Environment (SCOPE) presented a narrower range, from 100 to 200 EJ/year (SCOPE, 2015), while a recent review by Errera *et al.* (2023) projected 2050 potentials of 64, 313 and 1192 EJ/year for scenarios based on current conditions, optimistic assumptions, and full adaptation for the energy transition, respectively.

The magnitude of these figures can be better understood when compared to global energy consumption in 2020, which stood at 362 EJ, and bioenergy use at 45.6 EJ, of which 4.06 EJ came from liquid biofuels used in transport, as outlined in Chapter 1 (REN21, 2024). The SCOPE estimates, which sit roughly in the middle of the range between conservative and optimistic projections for 2050, suggest that bioenergy could account for around 28 to 55% of total energy use in 2020, and from 220 to 440% of that year's bioenergy consumption.

GRAPH 46. Global bioenergy sustainable production potentials



Source: Prepared by the authors.

As shown in Graph 46, the main conclusion to be drawn from these studies is that there is considerable potential to expand global sustainable bioenergy production—although the scale and feasibility of this expansion vary significantly, depending on how and where the biomass is sourced and processed.

The next section presents studies on the potential for sugarcane-based bioethanol production in regions particularly well-suited to this crop, offering more targeted and realistic results. These begin with an analysis of the potential of improving average productivity in agricultural production, introduce regional assessments and gradually move to country-level analysis, examining various production and processing system configurations and estimating the potential output of bioethanol and electricity from sugarcane.

8.1.2. Closing agricultural yield gaps: a sustainable pathway to scale up bioethanol production

This section was contributed by Agustin Torroba and Anabel Chiara, from the Inter-American Institute for Cooperation on Agriculture (IICA), based on their study Closing Agricultural Yield Gaps: A Key and Sustainable Alternative for Liquid Biofuel Supply *(Torroba & Chiara, 2025).*

A key strategy to sustainably increase global bioethanol supply lies not in expanding the agricultural frontier, but in closing the yield gaps of the main feedstocks used in its production: sugarcane, maize, and wheat. This pathway is agronomically feasible, environmentally sound, and socially beneficial.

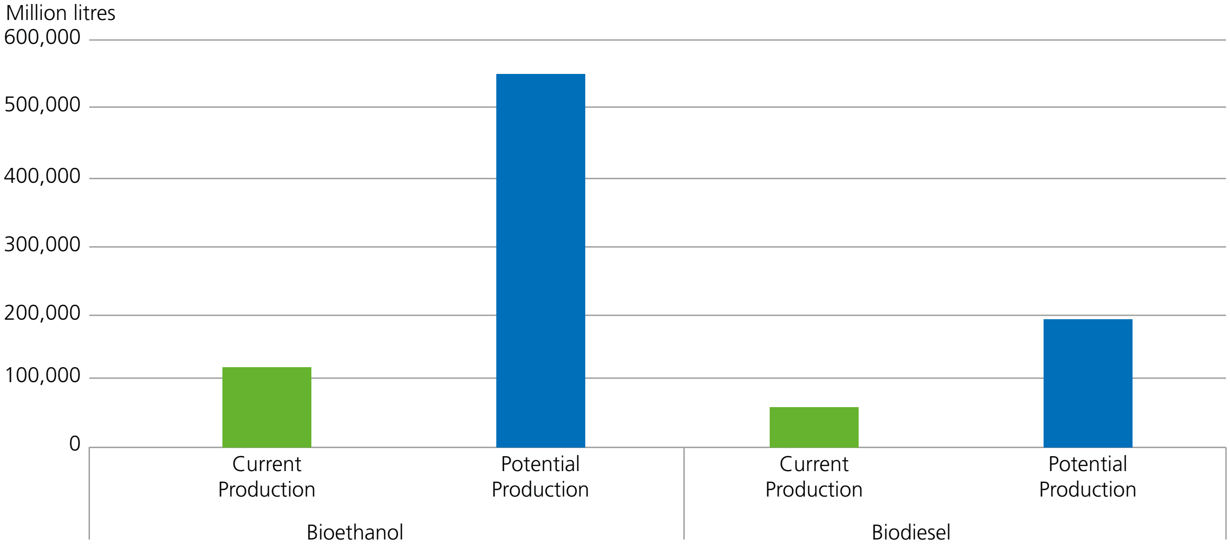
Currently, global bioethanol consumption is estimated at 2.3 EJ per year, within a total biofuels market of 4.6 EJ. Recent studies suggest that closing yield gaps in key crops—especially in regions of the Global South—could increase bioethanol supply to 14 EJ annually, without the need to convert new land. This level of production would comfortably cover global demand projections under deep decarbonisation scenarios to 2050.

Yield gaps refer to the difference between actual average yields and the potential yields achievable under optimal management and climatic conditions (Mueller *et al.*, 2012; Fischer *et al.*, 2014). Closing these gaps is a preferable alternative to land expansion due to the latter's risks in terms of deforestation, biodiversity loss, and GHG emissions (Pradhan *et al.*, 2015; Salazar *et al.*, 2024).

Rainfed agriculture, which represents 74% of global cultivated area, contributes only 44% of potential caloric output (Pradhan *et al.*, 2015). Gaps are especially pronounced in Sub-Saharan Africa, South Asia, and parts of South America, where they exceed 40% and can be recovered by appropriate interventions (Rosenzweig *et al.*, 2014). Underlying causes are diverse: water and nutrient constraints, low mechanisation, limited access to quality inputs, poor rural infrastructure, underdeveloped markets, exposure to climate risk, among others (Gatti *et al.*, 2023; Cherlet *et al.*, 2018). Bridging them requires a mix of agronomic technologies, infrastructure, financing, insurance, and sound public policy (Roser, 2024).

Closing the yield gaps for sugarcane, maize, and wheat could add over 550 million cubic metres of bioethanol per year—an increase of 372% compared to current production, as depicted in Graph 47. This expansion could be achieved without compromising food production or requiring new cropland.

GRAPH 47. Global current and potential bioethanol and biodiesel production



Source: Prepared by the authors based on Torroba and Chiara (2024).

To develop this sustainable potential, coordinated action is required across three areas:

- Public policies focused on productivity, via investment in rural extension, research, markets, and infrastructure.
- Access to technology and finance, especially for small and medium producers.
- Food-energy integration, recognising that closing yield gaps enables complementary production of food and fuel.

The ethanol industry operates as a multiproduct system that goes far beyond fuel production. Similar to oil refining, but based on renewable feedstocks, this model—sometimes referred to as "biomass cracking"—enables the simultaneous generation of energy, food, feed, and industrial co-products (Torroba, 2021; Trigo *et al.*, 2021). Each feedstock processed for ethanol—be it sugarcane, maize, or wheat—produces not only biofuel, but also a wide range of valuable by-products. For instance, maize ethanol production yields high-protein distillers grains (DDGS), maize oil, and biogenic CO_2; sugarcane-based ethanol generates electricity from bagasse, solid biofuels from cane trash, and even surplus sugar. These outputs help diversify income streams and distribute production costs more efficiently, improving the economic and environmental sustainability of the sector.

Crucially, these value chains reinforce food security rather than threaten it. The production of ethanol from crops like maize or sugarcane is closely integrated with the food and feed industries. A large share of the biomass is converted into high-protein animal feed—such as DDGS, soybean expellers, or canola meal—which supports livestock production and increases the availability of protein in food systems. Additionally, the circular nature of the industry allows for waste reutilisation and bioenergy generation, reducing pressure on land and input costs. Rather than displacing food, the expansion of bioethanol production through improved efficiency and integrated valorisation pathways can bolster both energy and food systems, especially in regions where agricultural productivity and diversification are key to sustainable development.

In conclusion, closing agricultural yield gaps is a cost-effective and sustainable strategy to scale up global bioethanol production. By improving the yields of traditional crops like sugarcane, maize, and wheat, countries can simultaneously advance food security, energy transition, and climate change mitigation—without compromising natural resources.

8.1.3. Bioethanol from sugarcane potential in Africa, Latin America and the Caribbean

This topic is based on the technical note prepared for this book by researcher Simone P. Souza from University of Campinas (UNICAMP).

Sugarcane presents a promising solution to energy needs in developing regions such as Southern Africa, Latin America, and the Caribbean. Research underscores its potential as a sustainable bioenergy source, offering cleaner energy and reducing reliance on fossil fuels (Magarey, 2020; Antwerpen *et al.*, 2013; Souza *et al.*, 2016; Souza *et al.*, 2018). As presented in previous chapters, its versatility, coupled with favourable growing conditions and existing infrastructure, positions sugarcane as an attractive option for modern bioenergy development in these areas. Efficient solar energy conversion and the potential for carbon dioxide recycling make sugarcane effectively relevant to global renewable energy demands.

Leveraging sugarcane's high biomass productivity and energy content can actually address escalating energy demands and mitigate climate change impacts across the Global South. As follows, bioethanol and cogenerated electricity production from sugarcane in these regions are assessed, considering two technology scenarios, and compared with the current energy demand in these countries.

Ethanol from sugarcane potential in Southern Africa

Sugarcane presents considerable potential for advancing cleaner and more accessible energy in Southern Africa, where the climate is favourable, and this crop is well known. Research conducted by Souza *et al.* (2016) evaluated two bioethanol production scenarios for Southern African countries: (1) a business-as-usual (BAU) scenario, where bioethanol is produced exclusively from existing molasses without expanding sugarcane production, and (2) a new framework (NF) scenario, where bioethanol is produced from both molasses and additional sugarcane (direct juice), cultivated on 1% of the current pastureland. The authors assessed the use of bioethanol as both a cooking fuel and a substitute for gasoline and diesel. The use of bioethanol in diesel engines is supported by Scania technology, which allows the use of pure bioethanol with 5% ignition improver in a diesel engine, as commented in Chapter 2. An increase in fuel and electricity consumption under the NF scenario is also assumed, in line with projections from the International Energy Agency (IEA, 2014).

As indicated in Table 20, in the BAU scenario, the use of existing sugarcane molasses for bioethanol production effectively contributes to meeting the energy needs of some countries. Under this scenario, for instance, bioethanol could satisfy up to 57% of household cooking energy demand or replace approximately 30% of fossil fuel consumption in Eswatini. The NF scenario could potentially meet up to half of Southern Africa's cooking fuel needs, drastically reducing reliance on traditional biomass sources like firewood. Programmes for introducing bioethanol stoves have been implemented in Kenya and Mozambique, with a large quantity of two burner stoves being distributed and good prospects for expansion, albeit not currently widely adopted. Implementing such strategies could save approximately 85 million tonnes of firewood annually and reduce forest exploitation by 145 million hectares by 2030 (IEA, 2014). The BAU figures for Angola were evaluated before deploying the BIOCOM sugar mill plant in September 2014, which significantly increased sugarcane molasses availability and will be discussed in detail later.

FIGURE 65. Bioethanol metal stoves displace firewood use and improve indoor air quality in Ethiopia (Project GAIA, 2025)

Photo: Harry Stokes/Project Gaia

TABLE 20. Potential bioethanol supply and fuel replacement in Southern African countries

COUNTRY	BAU SCENARIO (USING MOLASSES CURRENTLY AVAILABLE)				NEW FRAMEWORK SCENARIO (PRODUCING SUGARCANE IN 1% OF PASTURELAND)*			
	ETHANOL PRODUCTION (10^6 l/year)	COOKING FUEL	ETHANOL AS GASOLINE REPLACEMENT	ETHANOL AS DIESEL REPLACEMENT	ETHANOL PRODUCTION (10^6 l/year)	COOKING FUEL	ETHANOL AS GASOLINE REPLACEMENT	ETHANOL AS DIESEL REPLACEMENT
Angola	5	0%	0.24%	0%	1,727	69%	47%	26%
Malawi	27	2%	18%	13%	189	9%	72%	55%
Mauritius	37	-	16%	8%	38	34%	9%	5%
Mozambique	26	1%	8%	3%	2,197	69%	368%	168%
South Africa	184	4%	1%	1%	4,433	89%	16%	17%
Eswatini	51	57%	30%	31%	134	113%	45%	51%
Tanzania	43	1%	7%	3%	44	1%	4%	2%
Zambia	38	4%	9%	6%	1,748	99%	224%	159%
Zimbabwe	42	4%	13%	6%	874	49%	149%	80%

*The NF scenario accounts for the increasing fuel consumption rate and population. Bioethanol is not used as a cooking fuel in Mauritius because there is no tradition of using biomass for cooking.

Source: Adapted from Souza *et al*. (2016).

Moreover, sugarcane bagasse presents significant potential for electricity generation. By optimising the use of bagasse, Eswatini could substantially boost electricity production, with potential increases of 38% under the BAU scenario and 70% under the NF scenario.

Expanding sugarcane over pastureland not only promises cleaner energy but also significant reductions in greenhouse gas emissions. For instance, in South Africa, substituting coal-based electricity with bagasse could eliminate up to 4,800 kt of CO_2e emissions annually. Similar reductions are possible in Mozambique and Zambia, offering a substantial contribution to cleaner energy transitions.

While the initial investment in expanding sugarcane production may vary across countries, it represents a feasible endeavour relative to national economic capacities. However, challenges in financial feasibility remain, particularly in countries with limited capital resources. Thus, although sugarcane-based bioenergy presents a compelling opportunity for cleaner energy transitions in Southern Africa, it is contingent upon addressing technical, environmental, and financial challenges effectively.

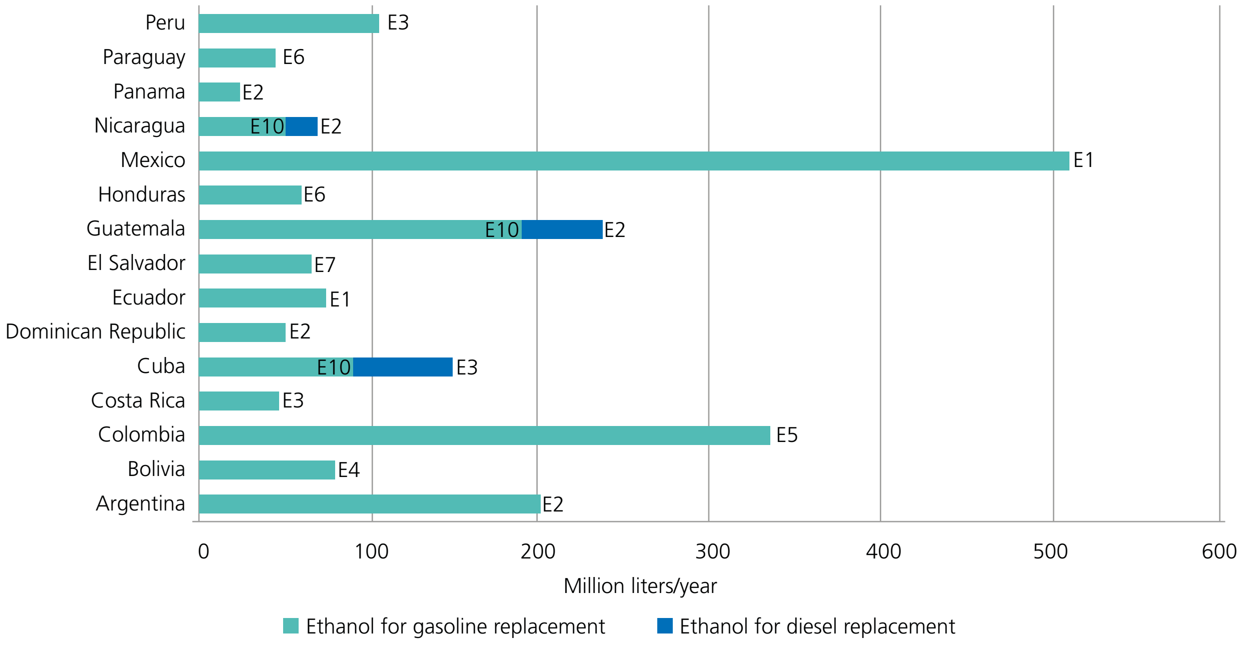
Ethanol from sugarcane potential in Latin America and the Caribbean

Similarly, Latin America and the Caribbean (LAC) exhibit considerable potential for sugarcane-based bioenergy. A study by Souza *et al.* (2018), employing the same BAU and NF scenarios as previously described for Southern African countries, demonstrates substantial benefits in both energy supply and greenhouse gas emission reduction. In this study, bioethanol was evaluated as a substitute for gasoline and diesel.

The results for the BAU scenario, summarised in Graph 48, indicate that the current availability of molasses in countries such as Nicaragua, Guatemala, and Cuba could replace up to 10% of gasoline and diesel consumption. Specifically, Nicaragua, a major importer of gasoline, could reduce its external dependency by 25% through bioethanol production. For the NF scenario, depicted in Graph 49 (in which the scale for bioethanol production is ten times greater than in the previous figure), countries such as Paraguay and Bolivia could potentially eliminate gasoline imports and substantially reduce their reliance on diesel by expanding sugarcane cultivation on only 1% of the available pastureland.

Moreover, optimising electricity generation from currently available sugarcane bagasse could address energy access gaps in countries like Colombia, Guatemala, and Mexico, thereby decreasing fossil fuel dependence and enhancing regional energy security. In the long term (NF scenario), bagasse could contribute up to 16% of Guatemala's and 7% of Colombia's national electricity supply, respectively.

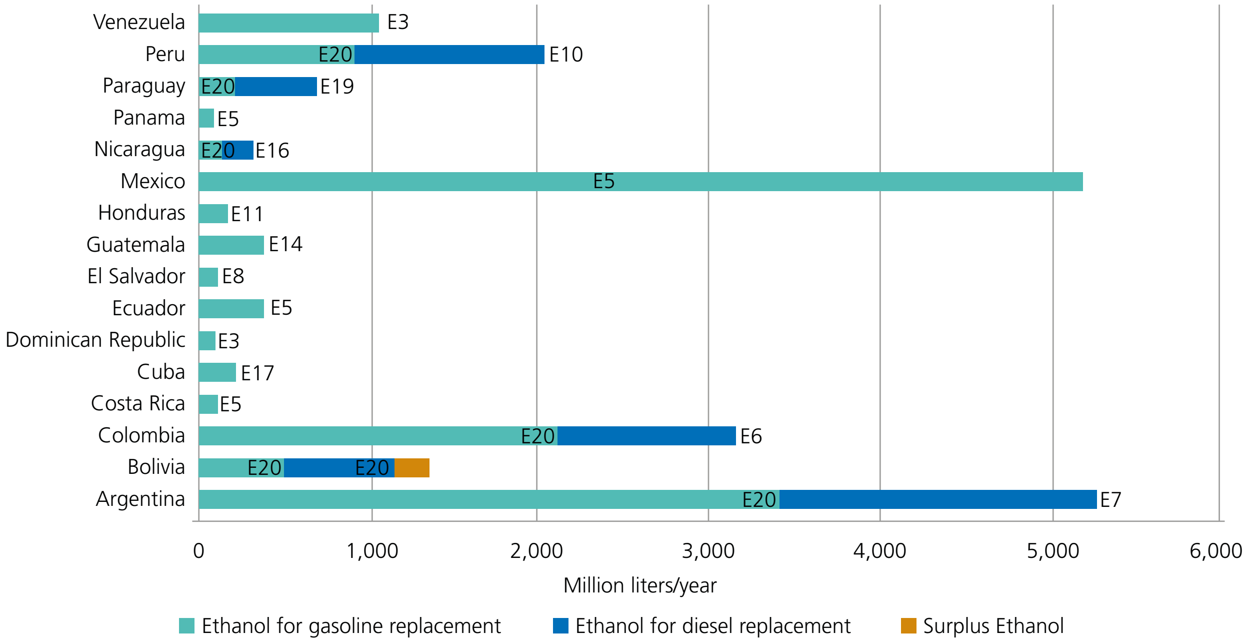
GRAPH 48. Potential bioethanol supply in Latin America—BAU scenario



Note: Venezuela's value is less than 1%.

Source: Souza, S.P. *et al*. (2018).

GRAPH 49. Potential bioethanol supply in Latin America—NF scenario



Source: Souza, S.P. *et al*. (2018).

Expanding sugarcane production across pastureland and deploying highly efficient cogeneration systems offers significant advantages in reducing greenhouse gas (GHG) emissions. A mere 1% increase in sugarcane production could lead to substantial emission reductions, particularly in countries heavily dependent on fossil fuels such as Bolivia, Paraguay, and Nicaragua. For instance, Bolivia could potentially achieve an 18% reduction in emissions by transitioning from gasoline and diesel to cleaner alternatives by 2030.

The total capital required for implementing these strategies in LAC, including sugarcane expansion and new processing facilities, is estimated at approximately USD 35 billion over a decade. While substantial, this investment represents a manageable fraction of national fixed capital investments in most countries. Overcoming financial barriers could be facilitated through foreign investments, particularly in economically constrained nations.

Challenges and opportunities

Developing sugarcane-based bioenergy in the Global South faces challenges. These include inadequate logistics infrastructure, a shortage of skilled professionals, complex land acquisition processes, human rights issues, and limited access to affordable financing. Addressing these challenges imposes robust policies prioritising societal welfare and sustainable resource management, integrating energy, agriculture, and rural development strategies.

Despite such challenges, this general appraisal of sugarcane potential for modern energy development in these countries makes evident that sugarcane holds a transformative promise for addressing energy needs sustainably across Southern Africa, Latin America, and the Caribbean. The expansion of sugarcane cultivation not only presents opportunities for economic growth, job creation, and rural development, but also promises substantial reductions in greenhouse gas emissions. Countries in these regions could significantly enhance their energy security through optimised use of sugarcane bagasse for electricity generation, thereby mitigating environmental impacts and advancing towards a more sustainable energy landscape.

While challenges in implementation persist, including financial constraints and infrastructural limitations, collaborative efforts and strategic planning offer pathways to realise the full potential of sugarcane bioenergy, paving the way for a brighter and greener future in these regions. To reinforce such a perception, it is necessary to explore the potential and opportunities more, at country level, as is developed in the following sections.

8.1.4. Bioethanol production potential: the IRENA studies

The main results of detailed studies assessing the potential for bioenergy production from sugarcane, promoted by the International Renewable Energy Agency (IRENA) for selected countries, are presented in this section. These studies identified the land suitable and available for bioenergy, employing geographic information system (GIS) tools and resources, and estimated sugarcane production using a yield model based on local climate data and considering rainfed and irrigated conditions, when applicable. In some cases, both sugarcane and energy cane were evaluated as feedstock. Conventional and advanced technologies for bioethanol and electricity production from sugarcane were studied. In addition to improving the technical foundations, these studies also introduced relevant economic indicators, such as the investment required and final cost.

Sugarcane bioenergy in Southern Africa

The report *Sugarcane Bioenergy in Southern Africa: Economic potential for sustainable scale-up* (IRENA, 2019), presented an evaluation of the technical and economic potential for seven sugar-producing countries in the Southern Africa Development Community (SADC): Eswatini, Malawi, Mozambique, South Africa, Tanzania, Zambia, and Zimbabwe, whose total population is around 198 million people (UN, 2024). The potential for both bioethanol and electricity production was evaluated, estimating in different scenarios the land dedicated to sugarcane and evaluating diverse processes, from using only molasses from the current and projected sugar demand for domestic consumption and export, to processing direct juice from sugarcane and, in the advanced context, processing lignocellulosic residues.

This assessment indicated that sugarcane cultivation covers some 569,000 hectares of land in the seven countries studied. Prospectively, cultivation could expand as much as eight-fold, to some 4.8 million ha (Mha) of rainfed land without irrigation, or 88-fold, to some 49.8 Mha of land if irrigation were introduced. These projections considered previous studies and incorporated criteria to ensure sustainability, including aspects such as protected areas, topography, and areas used to produce food and other products. For irrigated land, the Global Agro-Ecological Zoning (GAEZ) tool was applied, developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) (IIASA & FAO, 2012).

GAEZ assessment of suitable land requiring irrigation was conducted assuming that sugarcane should be produced only on soils classified as very suitable (VS), suitable (S), and moderately suitable (MS) for sugarcane. Areas shown by GAEZ as proper for rainfed sugarcane cultivation were not included to avoid double accounting. Suitable land for irrigated sugarcane was then evaluated in relation to its effective availability, considering three exclusion factors: current land use, protected and forest areas, and topography (slopes greater than 16%).

Applying this methodology, the current and potential suitable and available land for planting sugarcane in the studied countries is presented in Table 21. The sugarcane yield model based on climatic data, adapted from Beauclair (2014) and implemented for selected sites in the sugarcane zones in each country, allowed the estimation of the productivities presented in Table 22. For irrigated areas, no water deficit was assumed. The expressive gain in productivity when irrigation is used confirms the importance of this practice, mainly in arid zones. Combining the values of suitable and available land with yield estimates, the annual sugarcane production could be estimated.

TABLE 21. Current and potential suitable and available area (kha) for rainfed and irrigated sugarcane culture in selected Southern Africa countries

COUNTRY	AREA CULTIVATED WITH SUGARCANE (2014)	IRENA ANALYSIS BASED ON GAEZ			
		POTENTIAL RAINFED AREA	POTENTIAL AREA WITH IRRIGATION		
		VS + S + MS*	VS*	VS + S*	VS + S + MS*
Eswatini	57.8	-	-	-	-
Malawi	27.1	4	-	63	456
Mozambique	42.3	2,888	1,289	4,483	14,361
South Africa	246.9	57	603	2,591	9,374
Tanzania	198.5	1,694	138	1,688	8,067
Zambia	41.7	-	1,286	3,009	12,491
Zimbabwe	43.5	-	375	1,973	5,065
Total	**657.8**	**4,643**	**3,691**	**13,807**	**49,814**

*Soil quality: VS: very suitable; S: suitable; MS: moderately suitable.
Source: IRENA (2019).

TABLE 22. Sugarcane yields in Southern African countries with proper fertilisation, as function of climatic data (DD, rainfall, and HD) in selected sites

COUNTRY	SELECTED SITE	DD*	RAINFALL	HD**	YIELD (T/HA)	
		(°C DAY)	(MM)	(MM)	NOT IRRIGATED	IRRIGATED
Eswatini	Manzini	960	898	368	57.0	96.8
Malawi	Chileka	1,876	1,068	262	78.3	106.7
Mozambique	Xinavane	1,600	780	467	53.3	103.7
South Africa	Durban	604	935	342	56.0	92.9
Tanzania	Dodoma	1,196	658	595	35.0	99.3
Zambia	Lusaka	1,034	885	378	56.7	97.6
Zimbabwe	Harare	907	861	397	53.3	96.2

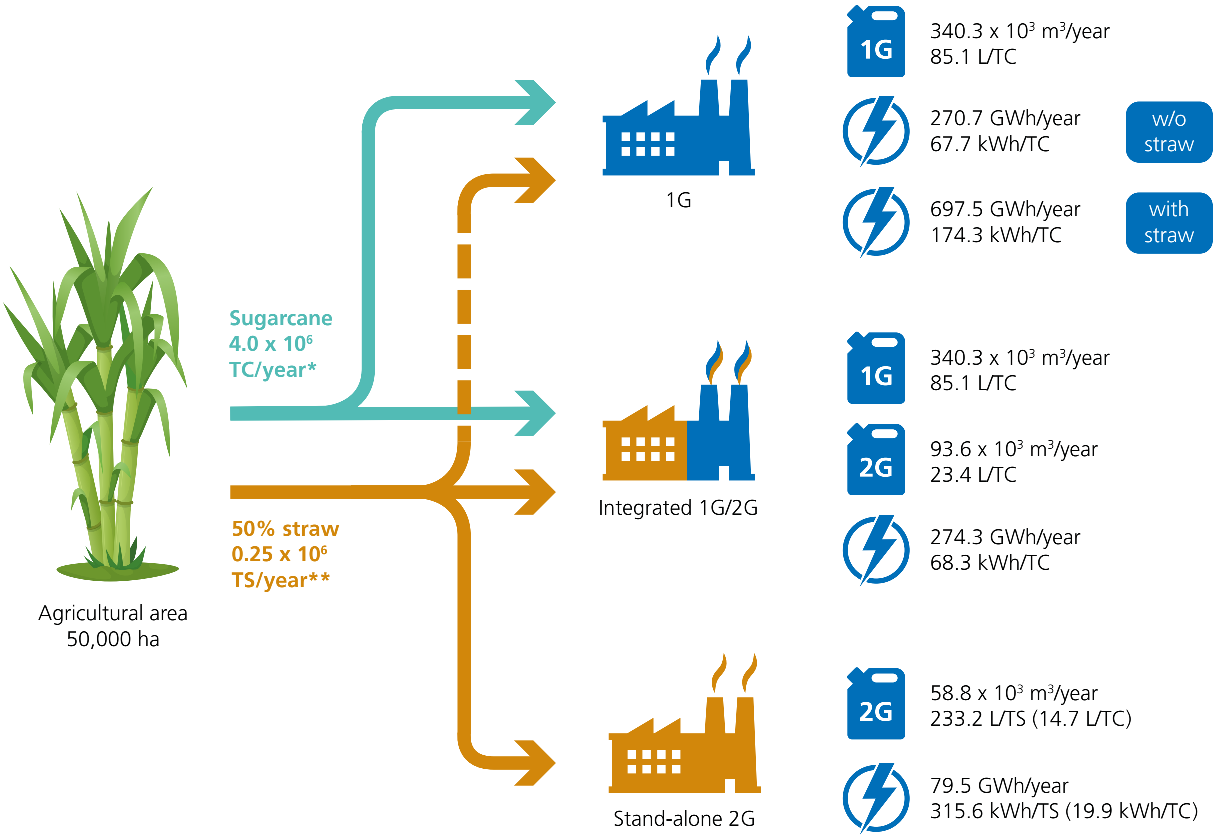
*DD: degree.days–intensity of warm days, when temperature is above 20ºC.
**HD: annual hydric deficiency, for 100 cm soil depth.

Source: IRENA (2019).

To assess the industrial phase, when sugarcane is processed, the following technical parameters are assumed (Leal *et al.*, 2016; Rein, 2007):

- Cane quality: sucrose 14% and reducing sugars 0.6% based on clean stalks, 5% vegetal impurities.
- Sugar production: 125 kg per tonne of sugarcane.
- Ethanol production from direct sugarcane juice: 85.4 litres per tonne of sugarcane.
- Bagasse production: 297 kg per tonne of sugarcane (moisture 50%; 14.1% fibre).
- Ethanol production from molasses with 42.1% total sugars as sucrose and 90% fermentation efficiency, with a yield of 260 litres of bioethanol per tonne of molasses. With 40 kg of molasses per tonne of cane, 10.4 litres of bioethanol are obtained per tonne of sugarcane processed for sugar.

FIGURE 66. Sugarcane plant configurations for 1G and 2G biochemical processes



*TC: sugarcane tonne.
**TS: bagasse and straw tonne.
Source: Adapted from CTBE (2017).

The technology options evaluated to process sugarcane for bioenergy and the main production indicators are shown in Figure 66 (CTBE, 2017). In this figure, 1G refers to the first-generation or conventional process producing bioethanol by fermentation of sugars; integrated 1G/2G refers to an integration of conventional and second-generation processes, processing lignocellulosic feedstock and sharing the same processes and utilities, and stand-alone 2G refers solely to a second-generation process.

To estimate the production cost of bioenergy in this context, the cost of sugarcane and the investment in the processing plant were evaluated. After considering different feedstock supply schemes (Leite *et al.*, 2016), the reference adopted for sugarcane price was that paid to efficient smallholder outgrowers in Mozambique: USD 24.4 per tonne of sugarcane at the mill gate, comparable to the Brazilian price paid to independent sugarcane producers.

The price of molasses was assumed to be USD 100 per tonne, an average historical value in this region.

The investment required for deploying sugarcane mills for bioenergy production was evaluated for brownfield and greenfield projects, each able to process 1.6 million tonnes of sugarcane per year. Plants producing both sugar and bioenergy, as well as those producing only bioenergy, were studied, with adoption depending on sugar production reaching a threshold defined by the domestic market and additional demand foreseen in each case. Additional details about the parameters and estimations are available in the full report (IRENA, 2019).

The main results of the estimated potential for producing bioethanol and electricity, along with the respective costs, are presented in Tables 23 and 24 for the main scenarios studied. In line with the evaluation of areas suitable and available for sugarcane production, three cases were considered, as indicated in Table 21: area currently cultivated, expansion in rainfed area, and expansion in irrigated areas.

TABLE 23. Bioethanol 1G production: potential and costs in 2015, considering the current sugarcane area and conventional processes

	ETHANOL FROM MOLASSES			ETHANOL DIRECT FROM SUGARCANE		
	POTENTIAL	COST		POTENTIAL	COST	
	(BILLION LITRES/YEAR)	(USD/LITRE ETHANOL)	(USD/LITRE GASOLINE EQUIVALENT)	(BILLION LITRES/YEAR)	(USD/LITRE ETHANOL)	(USD/LITRE GASOLINE EQUIVALENT)
Eswatini	0.06	0.34	0.49	0.00	0.48	0.68
Malawi	0.03	0.38	0.54	0.00	0.43	0.61
Mozambique	0.03	0.30	0.43	0.13	0.49	0.70
South Africa	0.15	0.42	0.60	0.76	0.48	0.68
Tanzania	0.03	0.49	0.70	0.46	0.53	0.76
Zambia	0.04	0.29	0.41	0.00	0.48	0.68
Zimbabwe	0.03	0.39	0.56	0.07	0.49	0.69
Total/Average	**0.37 (Total)**	**0.37 (Average)**	**0.53 (Average)**	**1.42 (Total)**	**0.48 (Average)**	**0.68 (Average)**

Source: IRENA (2019).

TABLE 24. Bioethanol 1G direct from sugarcane, potential production, and cost with improved yield and land expansion by 2030

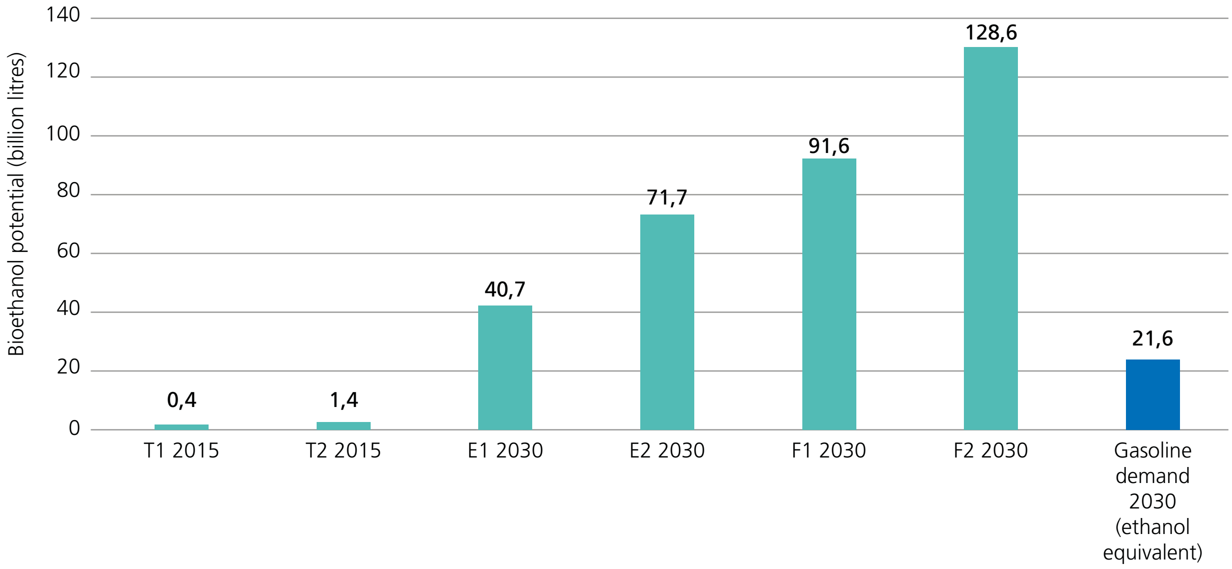
COUNTRY	POTENTIAL (BILLION LITRES/YEAR)			COST	
	CU*	CU + RF*	CU + RF + IR*	(USD/LITRE BIOETHANOL)	(USD/LITRE GASOLINE EQUIVALENT)
Eswatini	0.00	0.00	0.00	0.48	0.68
Malawi	0.00	1.56	1.56	0.43	0.61
Mozambique	0.02	20.10	31.38	0.49	0.70
South Africa	0.73	0.73	5.44	0.48	0.68
Tanzania	0.09	3.30	4.45	0.53	0.76
Zambia	0.00	9.95	21.25	0.48	0.68
Zimbabwe	0.00	4.61	7.65	0.49	0.69
Total/Average	**0.8 (Total)**	**40.2 (Total)**	**71.7 (Total)**	**0.48 (Average)**	**0.69 (Average)**

*Sugarcane area: CU: Area currently cultivated; RF: Expansion in rainfed area; IR: Expansion in irrigated area.

Source: IRENA (2019).

Summarising this assessment of the potential for ethanol production from sugarcane in these seven Southern African countries, Graph 50 presents the estimated total production of bioethanol for six scenarios, combining cases of area cultivated, processing technologies, and expected gains in productivity.

GRAPH 50. Six scenarios of ethanol potential in seven Southern African countries (scenarios presented in Table 25)



Source: IRENA (2019).

TABLE 25. Agroindustry technology and land-use scenarios evaluated

SCENARIO		YEAR	SUGARCANE AREA*	SUGARCANE YIELD**	INDUSTRIAL PROCESS***
T1	Today	2015	CU	SCC	1GM
T2	Today improved	2015	CU	SCI	1GM+1GD
E1	Expansion to rainfed land	2030	CU+RF	SCI	1GM+1GD
E2	Expansion to irrigated land	2030	CU+RF+IR	SCI	1GM+1GD
F1	Future process	2030	CU+RF+IR	SCI	1GD+2G
F2	Future process & feedstock	2030	CU+RF+IR	ENC	1GD+2G

*Sugarcane area:

CU: Area currently cultivated
RF: Expansion in rainfed area
IR: Expansion in irrigated area

**Sugarcane yield:

SCC: Current sugarcane yield, from FAOSTAT, the FAO database
SCI: Improved yield, from Sugarcane Yield Model, with proper fertilisation
ENC: Energy cane yield, 130 t/ha (Landell *et al.*, 2010)

***Industrial process for ethanol production:

1GM: Conventional process, from molasses
1GD: Conventional process, from direct juice
1GD+2G: Advanced, integrating ethanol conventional and 2G processes

Source: IRENA (2019).

With the expansion of sugarcane cultivation and the application of advanced technologies for both cultivation and conversion, the potential of ethanol would largely exceed the projected gasoline consumption in 2030, as indicated in Graph 50.

- If yields were improved on land already planted with sugarcane, about 1.4 billion litres of ethanol/year could be produced at an average cost of 0.71 USD/litre of gasoline equivalent, in addition to meeting domestic and export sugar needs.

- If sugarcane cultivation were expanded to all land suitable with natural rainfall, around 41 billion litres of ethanol/year could be produced, above Brazil's current production; and if it were further expanded to land suitable with irrigation, some 72 billion litres of ethanol/year could be produced, above current US production.

- With future application of advanced sugar cane technology on this land, about 92 billion litres of ethanol/year could be produced, and with further application of advanced conversion technology, about 129 billion litres/year could be produced.

Sugarcane bioenergy in Central America

Taking advantage of its favourable climate and land availability, sugarcane has been cultivated and processed in Central America since colonial times, representing one of the main economic activities in this region of seven countries: Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama. In this region exists a world class sugar agroindustry, which processed about 58 million tonnes of sugarcane in 2019. The total area of these countries covers 52.2 million ha, of which 35% corresponds to agricultural land and 4% to sugarcane fields (FAO, 2021).

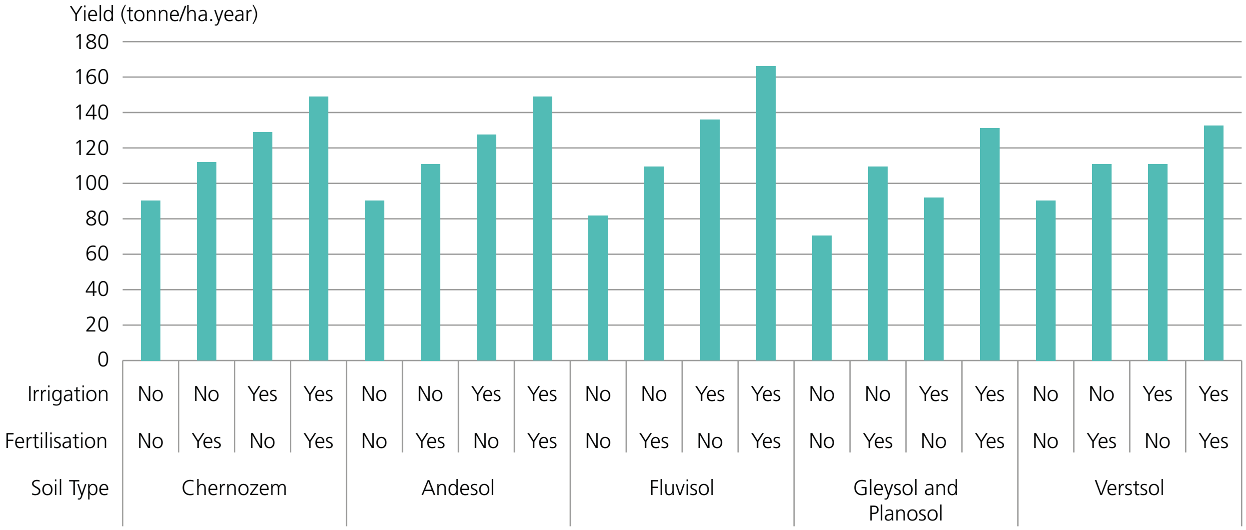
Despite the favourable natural conditions for implementing modern bioenergy production and use in Central America, reinforced by an active sugarcane agroindustry and the near total dependence on imported automotive fuels, this potential is still undeveloped, apart from a few limited initiatives. Therefore, to provide an assessment of sugarcane bioenergy perspectives, particularly with regard to the potential of ethanol production in this region, the same methodology presented for Southern African countries was adopted: select the feasible and available land, estimate sugarcane productivity, and then estimate the bioethanol potential (IRENA, 2022).

In this region, Guatemala stands out. It is the most important producer, responsible for more than half of total sugarcane production, with an average annual yield above 100 tonnes of cane per hectare. These results were achieved mainly by continuous and well oriented applied research in agriculture and industry, making use of local resources and developing efficient technologies. The Guatemalan Sugarcane Research and Training Centre (Cengicaña), created by the Guatemalan Sugar Association in 1992 to support the technological advance of the sugar agroindustry, is primarily responsible for this. The centre was funded by the Guatemalan sugar mills, which contribute to Cengicaña's budget in proportion to their sugar production.

Under these conditions, a more detailed approach was adopted to study Central America's potential for sugarcane production, considering the scale of cultivation, the maturity of the region's sugarcane agroindustry, the relatively homogeneous climate, and the availability of high-quality studies evaluating the effects of agricultural practices—such as irrigation and fertilisation—on sugarcane yield. Hence, the yield model incorporated the influence of soil quality, classified in six types, showing differential response to fertilisation and irrigation, the demand for which is also a function of sugarcane field altitude.

With these improvements, it was possible to estimate sugarcane productivity under the diverse conditions of Central America, as indicated in Graph 51.

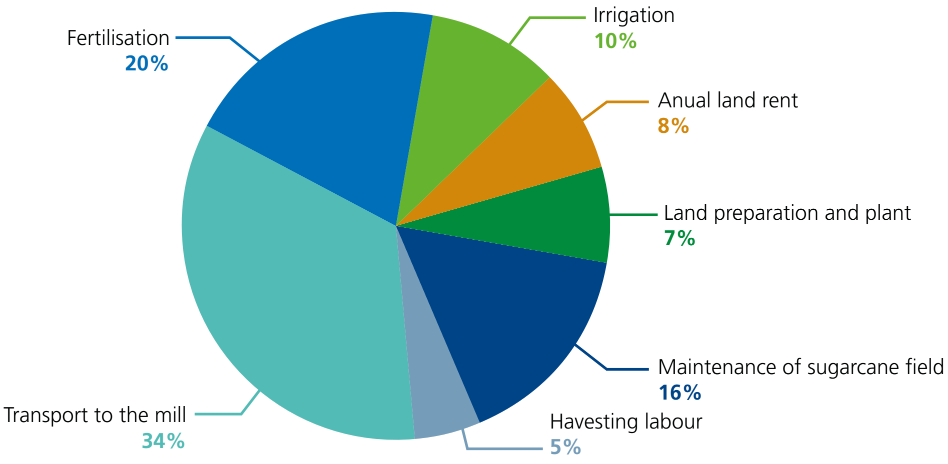
GRAPH 51. Indicative yield of sugarcane for different soils of Central America considering irrigation and fertilisation at recommended levels for low altitude plantation



Source: Prepared by the authors based on Melgar *et al*. (2012).

For cost estimates, a similar approach to that used for Southern Africa was adopted, based on actual historical costs, as shown in Graph 52 and Table 26 for the composition of sugarcane cost at mill gate in Guatemalan mills.

GRAPH 52. Composition of sugarcane production costs for a reference mill in Guatemala, 2020



Source: Adapted from Cutz *et al*. (2020).

TABLE 26. Total average costs of sugarcane production in low altitude Chernozem and Andesol soils areas in Central America

AGRICULTURAL TECHNOLOGY	YIELD (TONNE/HA)	SUGARCANE COST		COST COMPONENTS		
		(USD/HA)*	(USD/TONNE)	FERTILISER	IRRIGATION	TRANSPORT
no irrigation, no fertilisation	90	6,187	13.75	0%	0%	43%
no irrigation, fertilisation	111	8,919	16.07	19%	0%	37%
irrigation, no fertilisation	129	8,894	13.79	0%	12%	43%
irrigation, fertilisation	150	11,625	15.50	14%	9%	38%

*For the complete productive cycle, five years.

Source: Prepared by the authors based on Melgar *et al*. (2012).

Reference values of bioethanol cost are presented in Table 27 for four processing technologies, estimated assuming sugarcane cost at USD 15.50 per tonne, capital investment is annualised assuming a ten-year payment period and 10% weighted cost of capital.

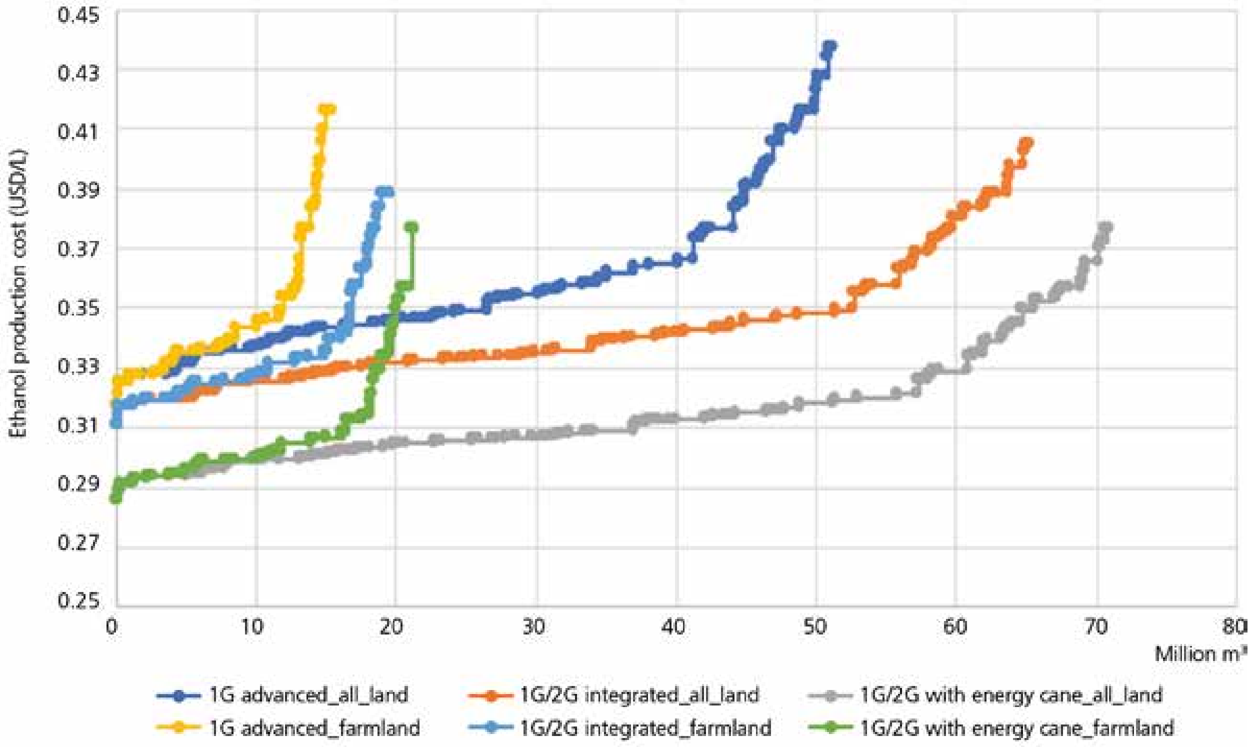
TABLE 27. Cost estimate of bioethanol from sugarcane in Central America, base case

TECHNOLOGY	FEEDSTOCK	FEEDSTOCK	CAPITAL AND O&M	TOTAL COST
			USD/LITRE	
Distillery in a brownfield mill	Molasses	0.327	0.195	0.522
Advanced 1G greenfield mill	Sugarcane + straw	0.182	0.109	0.292
Integrated 1G/2G mill	Sugarcane + straw	0.143	0.149	0.291
Integrated 1G/2G mill	Energy cane + straw	0.131	0.149	0.280

Source: Nogueira and Kang (2021).

With this detailed base of information and data, and applying similar productivities as adopted for Southern Africa, the bioethanol production potential in Central America could be presented as bioethanol supply curves. These curves relate the potential for bioethanol production to cost estimates; that is, there is a minimum production cost from which this biofuel can be produced, and a maximum potential for bioethanol production, determined by agronomic productivity limits and available land for cultivation on a sustainable basis. In this study, the land available was presented in three categories: (a) the farmland area freed up by increasing productivity, including the land currently under sugarcane and considering restrictions such as protected areas, land already occupied, topography, and soil quality; (b) a combination of rainfed and irrigated cultivation; and (c) a limited land expansion on pastureland, when feasible. The processing technologies included the conventional production of ethanol (from sugarcane molasses and direct juice) and two innovations: ethanol production from lignocellulosic hydrolysis (second-generation processes) and energy cane varieties, both able to increase significantly the energy yield in sugarcane fields.

GRAPH 53. Supply curves for ethanol from sugarcane in different land use and technology scenarios in Central America



Source: IRENA (2022).

Even for the moderate case using the freed-up farmland and 1G ethanol technology, the amount of ethanol able to be produced is sufficient to supply local potential consumption in blends up to E10, and the ethanol production cost in all cases is competitive, considering the average price paid to Brazilian producers in the last decade, which adopts the same technology (CEPEA, 2021).

These findings reinforce the favourable prospects for promoting bioethanol production in Central America, where the transport sector is the leading source of carbon emissions—25 $MtCO_2e$ in 2018, with 77% attributed to the fleet of cars and motorcycles (IRENA, 2022)—which can feasibly adopt this biofuel on a competitive basis and within a short timeframe.

Sugarcane bioethanol in the Caribbean SIDS

Small Island Developing States (SIDS) were recognised as a distinct group of developing countries at the United Nations Conference on Environment and Development held in Rio de Janeiro in 1992. Globally, SIDS, comprising 39 States and 18 Associate Members of UN regional commissions, confront unique social, economic, and environmental vulnerabilities, with a population of about 65 million people. Although there are significant differences between them, these nations share several particularities, which led the UN to recognise them as a group. Among these, dependence on fossil fuels, restricted industrial activity and limited economies of scale, vulnerability to natural phenomena, and fragile environments are commonplace.

The Caribbean, made up of nearly 7,000 islands, is a tropical maritime region encircled by the Caribbean Sea and the Atlantic Ocean. According to UNDP (2022), the Caribbean SIDS are a group of 26 members, mostly islands, and three continental lands (Belize, Guyana, and Suriname), including independent nations and colonies of European countries, with more than 39 million inhabitants, 90%, living in the five largest countries (Surroop *et al.*, 2018).

Oil products largely predominate in the energy matrix of Caribbean SIDS countries, representing a heavy burden on many local economies, with direct impacts on social, economic, and environmental conditions. Thus, the energy sector is crucial for the national development plans of these countries. Renewable energy sources are available in many countries, and their promotion could reduce reliance on imported energy, enhancing autonomy over energy markets. However, initiatives to adopt renewable energy have focused primarily on solar and wind systems, while transport continues to rely on oil products.

Seeking to strengthen the information base for decision-making and promotion of bioenergy in Caribbean SIDS, IRENA developed an assessment of its potential (IRENA, 2023); the section on bioethanol is summarised below. In total, six Caribbean SIDS were selected for this study: Cuba, Dominican Republic, Haiti, Jamaica, Trinidad and Tobago, and Guyana. These countries account for about 94% of the total area in this region and 93% of the total population.

The potential area for sustainable bioenergy crop production in the selected countries was 2.21 million hectares in 2019, estimated based on actual land use and coverage, and considering legal restrictions and environmental guidelines. This area is located mostly in three countries: Cuba (67%), Dominican Republic (15%), and Haiti (12%), representing a fraction of each country's land area: 14.2% in Cuba, 6.9% in the Dominican Republic, and 9.4% in Haiti. For the evaluation of bioenergy potential in the countries considered in this study, only a share of this land was adopted.

The potential annual production of sugarcane and its conversion into bioethanol was evaluated assuming average yields under four technological scenarios, in addition to land use. Considering the scenario of the current availability of molasses (distilleries attached to mills), total ethanol production in the islands studied was estimated at 880 million litres, of which Cuba contributes 67% and the Dominican Republic 19%. When considering an expansion of sugarcane cultivation areas and a state-of-the-art conversion process in the improved scenario (autonomous distilleries, improved sugarcane production), total potential ethanol production rises to 15.4 billion litres, with 77% corresponding to Cuba and 16% to Haiti. This biofuel production, except for Trinidad and Tobago and Jamaica, largely exceeds domestic gasoline demand in these SIDS. According to this study, adopting typical investment per mill and feedstock costs, bioethanol can be produced competitively, with costs ranging from USD 0.49 to 0.36 per litre. In fact, since 2008, Jamaica has been blending 10% bioethanol into gasoline, with positive results and benefits (NREL, 2020).

Despite this promising potential for sustainable development in Caribbean SIDS, these estimates represent an initial technical evaluation. Scenarios proposing further expansion of sugarcane cultivation require adequate assessment of relevant environmental and agronomic aspects, such as water availability and soil quality. Meanwhile, the production and use of bioethanol enables decarbonisation, reduction of polluting emissions from vehicles, and generation of income and rural employment.

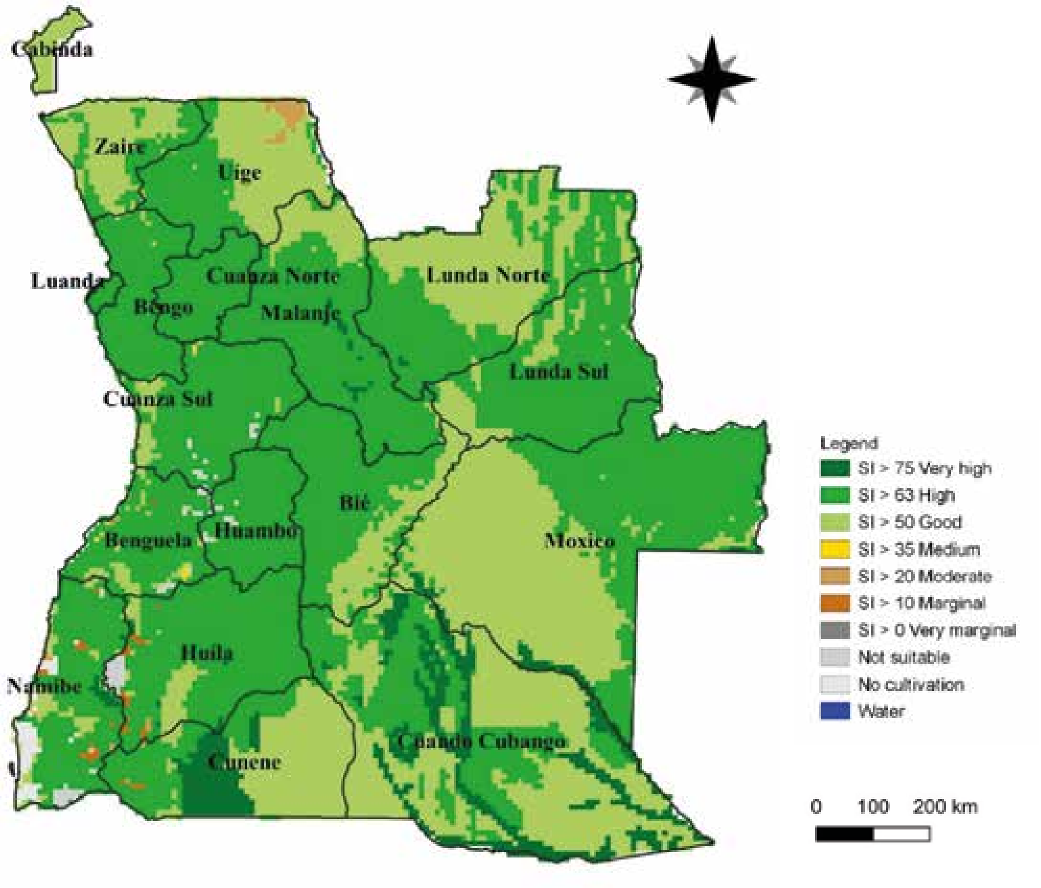
8.1.5. Sugarcane production potential: an evaluation of Angola

Located on the southwest coast of Africa, Angola covers an area of approximately 1.25 million square kilometres, making it one of the largest countries in Africa, with about 33 million inhabitants. Like other African countries, Angola faces challenges such as inequality, infrastructure deficits and post-civil war recovery efforts. It has abundant natural resources, including oil, which accounts for more than 70% of government revenues and more than 90% of the country's exports.

With a predominantly humid tropical climate and a large area for expanding agricultural activities, Angola has favourable conditions for bioenergy production, which has been proposed as an alternative for expanding the national energy system towards sustainability, improving environmental quality and living standards across the nation without compromising biodiversity and water use. In this sense, sugarcane, highly efficient in converting solar energy into biomass for energy, is the option of choice. These drivers have been recognised, and a modern sugarcane processing plant aimed at producing sugar and bioenergy was established in Angola. Crushing 2.2 million tonnes of sugarcane per year from a 38,000 ha plantation, it began operating in 2018 and employs around 32,000 people, directly and indirectly (BIOCOM, 2022).

To advance consistently in this direction, it is essential to know where and how much sugarcane can be produced in Angola. Thus, to evaluate the availability of suitable land for producing sugarcane, a method for data collection, processing, and analysis was implemented (Matias *et al.*, 2024). Initially, the global agro-ecological zones (GAEZ) database and Quantum GIS (QGIS) software were used to assess land availability for sugarcane cultivation in Angola, classifying the regions' suitability. Then, based on the FAOSTAT database, areas with restrictions such as protected zones, land already used for other crops, slopes higher than 16%, and soils unsuitable for sugarcane were excluded. Finally, an agricultural yield model was used to estimate the potential yield of sugarcane based on climatic parameters and the amount of bioenergy (bioethanol and bioelectricity) that could be produced on the available land.

FIGURE 67. Angola: sugarcane suitability index under irrigated conditions, before excluding areas with restrictions



Source: Matias *et al.* (2024).

Under these criteria, this study identified 6.3 Mha of land classified as very suitable and top quality suitable, with sufficient water resources, corresponding to 5% of Angolan territory. These areas are distributed across seven provinces, particularly Cuando Cubango and Cunene, where 85% of the very suitable land under irrigation is located. Assuming irrigation and adequate agricultural practices, such an area could produce approximately 956 million tonnes of sugarcane annually, significantly higher than the current production in this country. This amount of feedstock, processed using current technology, could potentially yield 81.3 billion litres of bioethanol and 176.9 TWh of electricity with low GHG emissions per year. As a whole, this could mitigate around 60.3 MtCO_2e annually by replacing gasoline in light vehicles in Angola and other countries, as well as diesel and natural gas consumed in power generation (Matias *et al.*, 2024).

This assessment demonstrates there are currently powerful computational resources and highly detailed, freely accessible georeferenced databases that allow for robust estimations of potential bioenergy production at national level.

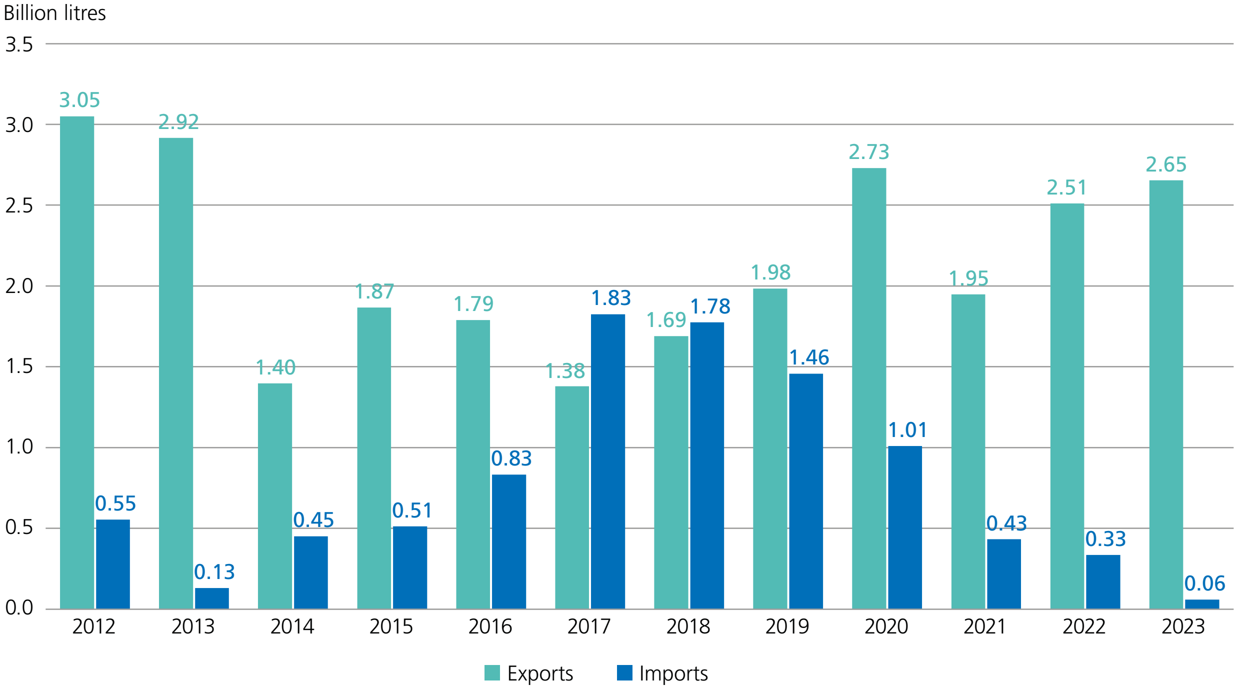
8.2. Global bioethanol market

As the supply of bioethanol is directly dependent on agricultural production, and therefore subject to seasonal variation, the potential for trade between producer countries with occasional surpluses and consumer countries with limited domestic supply is a key factor in stabilising the market. Despite ongoing protectionist practices in certain markets—characterised by significant trade barriers and high tariffs on biofuels, often taxed as agricultural commodities while petroleum and its derivatives are generally tax-exempt—international bioethanol trade has grown substantially. This expansion has reached a significant business volume and holds promising prospects for continued growth in the coming years. The current upward trajectory of the market suggests a positive outlook for its consolidation in the near future.

Bioethanol trade between countries, typically involving the United States and Brazil, was valued at USD 71.8 billion in 2024, with projections indicating growth to USD 110.7 billion by 2032. This represents a projected compound annual growth rate (CAGR) of 4.6% over that period (Fortune Business Insights, 2024). These forecasts appear realistic and are aligned with projections for the share of biofuels in global energy consumption for the transport of people and goods—currently at 4% and expected to reach 6% by 2030 (IEA, 2024d). At present, international trade in bioethanol accounts for 4.7% of the global petroleum industry's trade volume, which has been estimated at around USD 1.5 trillion in recent years (UN, 2025).

The two largest bioethanol-producing countries—the United States and Brazil—are also the main exporters. In 2024, they exported 6.9 and 1.9 billion litres, respectively. In years with favourable harvests and lower sugar export prices, Brazil's exports have been higher, reaching three billion litres in 2012, as shown in Graph 54. In 2024, Brazil's principal export destinations were South Korea (33.3% of total volume), the United States (17.4%), the Netherlands (15.9%), and the Philippines (6.2%). In 2023, the main importers of US bioethanol were Canada (44.7%), the United Kingdom (11.2%), the Netherlands (8.0%), South Korea (6.6%), and India (6.5%) (EIA, 2024b; EPE, 2024b). Today, over sixty importing countries participate in the global bioethanol market, which is increasingly served by trading companies that traditionally dealt only in petroleum derivatives but have in recent years added liquid biofuels such as bioethanol and biodiesel to their portfolios, thereby connecting producers with consumers.

GRAPH 54. Brazilian bioethanol exports and imports



Source: EPE (2024b).

A significant recent development for the global bioethanol market has been the independent certification of sustainability across the entire production chain—from field operations to end use. In this regard, the Bonsucro platform, dedicated specifically to sugarcane, has developed a protocol for auditing environmental and social compliance across five core areas: management, environment, labour, best practices, and infrastructure. This framework comprises 20 criteria and 69 indicators, establishing a global standard for assessing the sustainability of the sugarcane-ethanol agroindustry (Neves & Kalaki, 2020).

As of 2024, 167 agro-industrial units across all continents—though not all bioethanol producers—were Bonsucro-certified, with 54% located in Brazil. Bonsucro-certified plants in Brazil process sugarcane cultivated over approximately two million hectares and account for 95% of all certified-sustainable bioethanol consumed globally (Bonsucro, 2025). In October 2024, Brazil's National Petroleum Agency (ANP) and Bonsucro signed an agreement to integrate the Bonsucro and RenovaBio certification schemes, thereby reinforcing both programmes, which share aligned objectives. The integration aims to establish a unified procedure covering: (1) the criteria that sugarcane ethanol producers must meet; (2) data input, calculation and information management requirements; (3) the development of an integrated tool; and (4) criteria for certifying bodies (covering planning, execution, and post-audit processes). This integration could extend the applicability of the National Biofuels Policy (RenovaBio programme, introduced in detail in Chapter 7), strengthening bioethanol's contribution to global energy sector decarbonisation.

New fuel ethanol markets are emerging and may represent significant demand in the coming years, particularly in heavy-duty transport using diesel engines and in sustainable aviation fuel (SAF) production—topics addressed in earlier chapters. Non-energy markets already account for considerable demand, particularly in the chemical and food industries, where bioethanol's physicochemical properties and lower toxicity make it a favourable alternative to traditional feedstocks. Brazil's largest bioethanol importer, South Korea, is currently evaluating its use as a fuel, although it is presently used solely as an industrial input.

The following section presents perspectives from countries that have implemented or are planning to implement domestic bioethanol markets under varied conditions and outcomes, offering valuable lessons.

8.3. National initiatives for bioethanol use

The recent resurgence of interest in bioethanol as a sustainable and competitive fuel source is unfolding unevenly across countries due to differences in local information, motivations, and available resources. Nevertheless, the current growth in bioethanol use in some ways echoes the pioneering era of this biofuel. As described by Kovarik (2006), bioethanol was widely used in the early days of motorised transport, particularly in the United States, Western Europe, various Latin American countries, and some Asian and African nations—a scenario not dissimilar to the one depicted in Figure 5, showing countries that have adopted bioethanol.

This section briefly reviews the outlook in countries that have recently adopted, or are on the cusp of adopting, bioethanol as a regular component of their fuel markets. It begins with a summary of the situation in Latin America—a region where, with a few notable exceptions, bioethanol is used in nearly every country. Then it is considered two exemplary nations: Guatemala, which has been striving for over three decades to use domestically produced biofuel in its vehicles rather than exporting it; and India, where the government swiftly mandated the nationwide introduction of E20. Finally, drawing from countries with established or emerging national bioethanol programmes, a summary of key lessons learned is presented.

8.3.1. An overview of biofuels in Latin America and the Caribbean

Latin America and the Caribbean are among the best positioned regions to promote biofuel markets, as they possess suitable and abundant natural resources, rely significantly on automotive fuel imports, and have accumulated extensive experience in the bioenergy agroindustry (OLADE, 2025). Recently, the Inter-American Institute for Cooperation on Agriculture (IICA), through its technical report on the institutional and regulatory frameworks for liquid biofuels, has mapped the legislation and public policies in place across Latin America and the Caribbean (Torroba & Chiara, 2024). According to this study, nine countries in the region currently have effective mandates, and three additional countries are close to implementing blending mandates for bioethanol in their gasoline supply. Chart 5 summarises the most recent legislation and regulatory instruments that support the adoption of ethanol as a component of national energy and agricultural strategies.

CHART 5. Regulatory frameworks and reference ethanol blend levels in Latin American and Caribbean implementation programmes

COUNTRY	BIOETHANOL CONTENT	MAIN LEGAL FRAMEWORK
Countries with effective blends		
Argentina	12%	Ley Nº 26.093/2006 and Ley Nº 27.640/2021
Bolivia	25%	Decreto Supremo Nº 5.135/2024, raising the blend from 12% to 25%, with a progressive implementation schedule
Brazil	30%	Lei Nº 13.576/2017 and Lei Nº 14.993/2024
Colombia	10%	Resolución 40447/2022
Ecuador	5%	Decreto No. 675/2015
Jamaica	10%	National Biofuels Policy 2010-2030, 2008
Paraguay	30%	Ley Nº 2.748/2005 and Decreto 3.241/2025
Peru	7.8%	Ley Nº 28.054/2003 and Decreto Supremo Nº 013/2005
Uruguay	8.5%	Ley Nº 18.195/2007
Countries with legislative progress and close to implementing ethanol blending mandates		
Costa Rica	10%	Plan Nacional de Desarrollo 2023-2026
Guatemala	10%	Acuerdo Gubernativo Número 159-2023 establece los lineamientos para la efectiva aplicación del Decreto número 17-85
Panama	10%	Article 2, Ley Nº 355/2023

Source: IICA (2024).

Most countries have advanced in proposing laws and regulations mandating bioethanol blending in gasoline, with varying blend levels and implementation timelines. The most commonly adopted blend is E10 (10% ethanol), also the global norm, although some countries use higher concentrations—Paraguay, for example, is a global pioneer in adopting E30, while Guatemala plans to start with 5% in 2026.

These legal frameworks differ in how mandates are applied, including timelines for phased implementation and geographic coverage. Typically, mandates apply to all gasoline sold in a country, though in some cases—such as Ecuador—specific fuels have been created, such as the ECOPAÍS gasoline introduced in 2009, containing 10% ethanol and sold in major markets.

It is worth noting that blending mandates are not always compulsory. For example, in some cases the legislation merely authorises the addition of up to 10% ethanol to gasoline, while in most countries the law requires that, from a given date, all gasoline sold contain between 9% and 11% ethanol. Permitting use on an optional basis has a very different effect from requiring it, and thus clear data on actual ethanol consumption is not always available.

The diversity observed in how Latin American and Caribbean countries design and implement ethanol blending mandates reflects local conditions and priorities. Nonetheless, a few general considerations are worth noting:

- The legal framework for promoting bioethanol must clearly define fuel quality standards, which are essential to counter lingering misconceptions and doubts about ethanol use. Suitable specifications for both ethanol and its gasoline blends are critical, and harmonising national standards is highly desirable.
- Strengthening national technical capacity to monitor fuel quality is essential and has seen progress in Central America (CEPAL, 2006).
- Maintaining consistent ethanol blend levels is important. Where changes are necessary, they should be implemented gradually. Abrupt changes have proven difficult to recover from.

The diverse Latin American experience shows that attempts by some governments to embed multiple broad objectives within the legal framework for introducing fuel bioethanol—such as mandating local production using only domestic raw materials, setting limits on bioethanol imports and exports and fixing prices throughout the supply chain from producers to end consumers—often end up hindering its implementation. Across most of Latin America, countries rely on imported gasoline, with prices largely determined externally. Imposing restrictions and conditions on the production of biofuels undermines their viability, particularly in new and still-developing markets. In this context, the truly critical factors are ensuring sustainable production and avoiding tax regimes that disadvantage ethanol. When these conditions are met, ethanol markets can develop healthily, attract investment, and deliver the expected socioeconomic benefits (Cantarella *et al.*, 2023).

8.3.2. Guatemala: where the fuels of the future are still waiting to arrive

Guatemala, with an area of approximately 109,000 km^2 and a population of 19 million, along with a rich cultural heritage, is one of the global leaders in sugarcane and sugar production technology. In the 2023/2024 agricultural year, Guatemala ranked as the second most efficient sugarcane producer and the fourth most efficient in sugar production overall (USDA, 2025). The high technological standards of the Guatemalan sugarcane agro-industry have already been discussed earlier in this chapter, in the context of Central America's sugarcane expansion potential.

With 270,000 hectares under sugarcane cultivation, the 2024/2025 harvest yielded 2.62 million tonnes of sugar, of which 1.29 million tonnes (49%) were exported. These figures place Guatemala among the top ten sugar exporters globally. In addition to sugar exports worth USD 729 million, Guatemala exported 183.2 million litres of bioethanol, valued at USD 110 million, with the Netherlands, Puerto Rico, Sweden, and Mexico among the main buyers (USDA, 2025).

Gasoline consumption in Guatemala has grown substantially, reaching approximately 2.316 billion litres in 2023 (EIA, 2024a), all of it imported, making it the country's leading import item. The exported volume of bioethanol is equivalent to 128.2 million litres of gasoline, meaning Guatemala could immediately adopt an E5 blend—or even E10. The country has been producing and exporting bioethanol for over three decades, and the installed production capacity at Guatemalan mills currently stands at 246 million litres per year (ACR, 2024). One must then ask: why does Guatemala not use its own bioethanol?

Various studies and assessments by independent consultants, local organisations, development banks, and multilateral agencies have consistently concluded that using this renewable, domestically-produced biofuel is feasible and should be promoted. Paradoxically, however, while initiatives are undertaken, they rarely progress—some stakeholders, fearing negative impacts, prefer to maintain the status quo of fossil fuel consumers (Cutz *et al.*, 2020). Nevertheless, hope remains, as the potential benefits are considerable.

In July 2023, Governmental Agreement 159/2023 was enacted, replacing Governmental Agreement 420 of 1985, which regulated the Alcohol Fuel Law approved 40 years earlier but never implemented despite numerous attempts. The new legal framework—another step in the right direction—aims to "develop and standardise procedures for the production, storage, handling, use, transport, and commercialisation of fuel alcohol and its blends, as well as the administrative responsibilities of the Ministry of Energy and Mines" in this area. In line with this mandate, the Ministry determined that a 5% ethanol blend (E5) in gasoline should become mandatory from January 2025. However, despite this modest level—while dozens of countries already use E10—the initiative was not implemented. Once again, pressure from certain sectors led to calls for revision, particularly to remove the compulsory nature of the measure. It was ultimately decided to reopen the discussion and postpone the adoption of E5 to January 2026.

There is no doubt that using Guatemalan bioethanol in the country's own vehicles is a desirable and achievable goal, with wide-ranging energy, economic, social, and environmental benefits, as demonstrated by the practical experience of many countries. There are absolutely no technical constraints preventing widespread use of E10 in Guatemala. Sadly, however, misinformed opponents have managed to derail progress by spreading false information and scaremongering about non-existent risks—especially for vehicles. As one Guatemalan academic put it: "the challenge is getting everyone to agree" (Zambrano, 2025).

8.3.3. India: where the fuels of the future have already arrived

Sugarcane has been cultivated in India for thousands of years, and through successive crossbreeding it has evolved into a highly productive crop, making it one of the most suitable for energy purposes. At present, sugarcane occupies around five million hectares (1.5% of the country's land area), enabling the annual production of approximately thirty million tonnes of sugar. This makes India one of the world's largest producers and exporters.

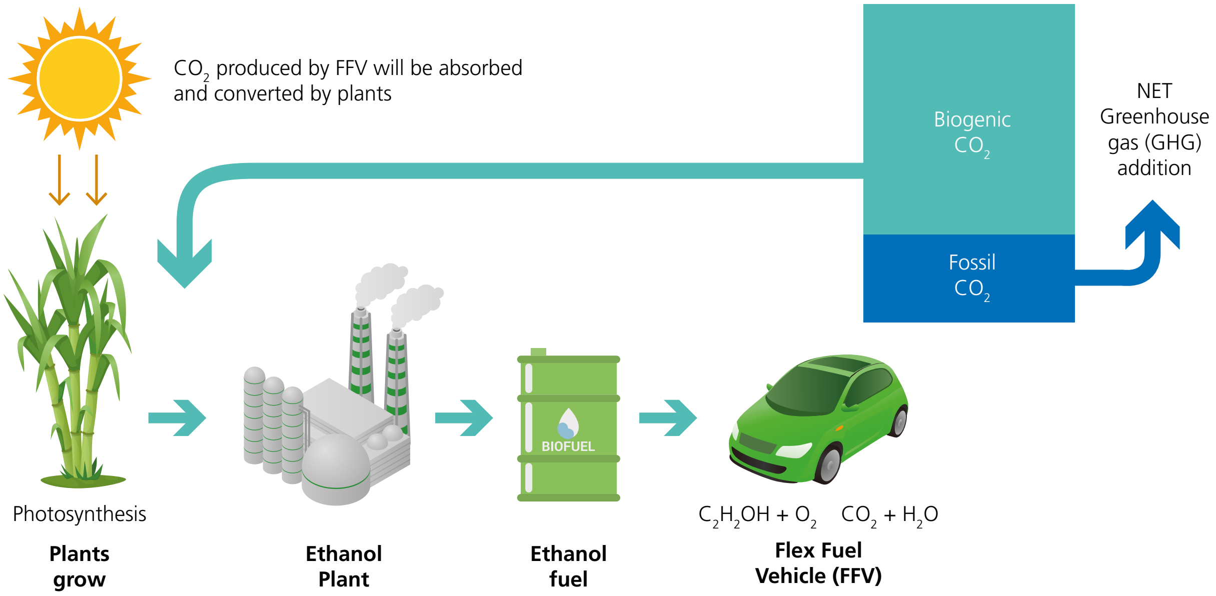
As in Brazil, the use of sugarcane for producing vehicle fuel in India dates back to the early days of the automobile. Kovarik (2006) and Saranavan *et al.* (2018) document notable developments. A 1919 report from the UK's Alcohol Motor Fuel Committee identified India as a potential source of motor fuel. In 1938, a provincial committee in Uttar Pradesh and Bihar recommended sugar mills convert molasses into alcohol, rather than using it as fertiliser. By 1940, Uttar Pradesh had enacted legislation requiring a 20% alcohol blend in gasoline, followed by several other provinces. Pure bioethanol was widely used during the Second World War as an emergency measure—by 1943, gasoline shortages had brought transport to a halt. Around eight million litres were used in 1946, rising to nine million in 1948. A further 20 million litres were blended with gasoline, which amounted to around a billion litres annually by 1951. The Indian Power Alcohol Act of 1948 set out a 20% blending requirement where feasible, but it was never widely implemented. Like most countries, India eventually abandoned bioethanol in favour of gasoline—until recently.

India is now the third-largest energy consumer in the world and has traditionally relied on imported oil to meet its growing energy demands, projected to exceed seven million barrels per day by 2030 (Eximpedia, 2025). This dependency—currently around 88%—poses a threat to energy security and has led to a substantial outflow of foreign currency, exceeding USD 130 billion annually in recent years. With the adoption of bioethanol as a fuel, India aims to reduce its dependence on imported energy and promote sustainable rural development, along with environmental gains. Produced from domestic feedstock, bioethanol can be used without changes to the existing fuel infrastructure or to the roughly 300 million vehicles on India's roads—a diverse and growing fleet.

With this objective, ethanol blending resumed in 2001 with a pilot project, expanded in 2003 under the Ethanol Blended Petrol (EBP) Programme, although initial outcomes were limited. The decisive turning point came in 2018 with the National Policy on Biofuels, led by the Ministry of Petroleum and Natural Gas, which set ambitious targets for increasing ethanol content in gasoline. Originally, the goal was to achieve E20 by 2030, but in 2020 this was brought forward to 2025, reflecting the government's commitment to accelerating ethanol adoption. By 2022, E10 had been rolled out nationwide, and by late 2024, all gasoline sold in India was E20. An impressive outcome indeed.

In the 2013/2014 agricultural year, India produced 0.38 billion litres of bioethanol. This figure rose to 3.02 billion litres in 2021 and reached 16.23 billion litres in 2024—a remarkable increase that comfortably exceeded the target (INDIA, 2024). Bioethanol has now been fully integrated into India's energy matrix, and its share continues to grow, with flex-fuel vehicles expected to be introduced in the coming years, as shown in Figure 68.

FIGURE 68. Environmental benefits of bioethanol in flex-fuel vehicles, as promoted by an automaker in India



Source: Adapted from Maruti Suzuki (2022).

In just a decade, since 2014, India's ethanol blending programme has generated substantial benefits: saving USD 163 billion in foreign exchange, cutting CO_2 emissions by 54.4 million tonnes, and replacing 135 million barrels of oil. Additionally, the programme has had a significant economic impact in rural areas, with fuel distributors disbursing the equivalent of USD 2.25 billion to distilleries and USD 1.35 billion to farmers (INDIA, 2024).

It is worth noting that India's success in integrating bioethanol was made possible by strong support from the scientific community, which contributed through programme evaluation, research into new technologies, processes, and feedstocks, and by pushing the boundaries of bioenergy innovation. Equally important was the enthusiastic backing of the automotive industry, which rightly recognised bioethanol as a major opportunity for growth in a new environment—one likely to be replicated in similar contexts around the world.

8.4. Bioethanol logistics

In addition to the usual logistical challenges involved in transporting petroleum-derived liquid fuels—particularly the large volumes and long distances—bioethanol presents at least two additional complexities: material compatibility (as discussed in Section 2.2.5: *Compatibility with automotive materials*) and seasonal production.

In the case of sugarcane-based bioethanol, the raw material must be harvested at peak sugar content and cannot be stored at the mill, as the sugars rapidly degrade. Therefore, processing must take place during the harvest period, which typically lasts between seven and ten months in south-eastern Brazil, the country's main producing region. While demand for bioethanol also fluctuates seasonally, it is crucial that average monthly production capacity exceeds monthly consumption, allowing for sufficient stockpiling to cover the industry's off-season.

Imports during the off-season and the growing production of bioethanol from maize—which can be stored for several months—have helped ease the pressure on storage capacity, though they have not eliminated the need altogether. Inventories must still be established with a margin of safety above the estimated demand for the period.

For the 2023/2024 harvest, Brazil's total output of bioethanol (anhydrous and hydrated combined) reached nearly 36 million cubic metres. In 2023, the country's total storage capacity for bioethanol stood at 18.3 million m^3—equivalent to 51% of annual production—across primary storage and distribution facilities. Of this capacity, 68% was dedicated to hydrated ethanol and 32% to anhydrous, with a small share allocated to other types of alcohol. The Southeast—Brazil's leading region for both production and consumption—accounts for 11.1 million m^3, or 61% of total storage capacity, followed by the Central-West, the second-largest producer, with 28% (EPE, 2024b).

8.4.1. Modes of transport for bioethanol

Given the considerable distances between production sites, consumer markets, and export ports, bioethanol transport can consume significant amounts of energy and generate notable carbon emissions. It is therefore important to assess the environmental impact of different transport modes. On land, bioethanol can be moved by rail—more common in the United States—or by road, which predominates in Brazil. These are complemented by inland waterways and pipelines.

For international shipments—except to neighbouring countries, where road and rail transport can be used—bioethanol is typically transported in tankers, generally with capacities between 30,000 and 50,000 m^3, though larger vessels capable of carrying 100,000 m^3 or more are also in operation. Tankers are fitted with isolated compartments, enabling them to carry different products without cross-contamination. Efficient and safe loading and unloading require compatible onshore terminals, with facilities designed to match the scale of operations and ensure product integrity.

In Brazil, virtually all international bioethanol trade in 2023 was conducted by sea—99.8% of exports and all imports. The Port of Santos handled 89.6% of total exports, followed by the Ports of Paranaguá and Rio de Janeiro. On the import side, the main entry points were the Ports of Suape and Rio Grande (EPE, 2024b).

For large volumes and long distances, pipelines offer the safest, most reliable, cost-effective, and environmentally sound method for transporting liquid fuels. However, for many years, bioethanol was considered an aggressive substance, associated with corrosion in metallic materials and swelling or embrittlement of elastomers used in seals. These concerns have since been addressed through improvements in coatings, surface treatments, and tighter controls on ethanol specifications—particularly limits on certain ions—making it possible for bioethanol to be safely transported through pipelines, like other liquid fuels (Paes, 2024). These pipelines may be dedicated exclusively to bioethanol or may be multi-product pipelines, in which ethanol is transported in batches alongside other fuels. In such cases, special precautions are taken when handling pure bioethanol or gasoline with high ethanol content. According to the American Petroleum Institute, existing pipelines can carry gasoline with up to 15% ethanol (E15 or below) without requiring changes to design or operational procedures (AOPL & API, 2010).

Since 2016, the integrated bioethanol logistics system developed by the company Logum has been under construction and has been partially operational since 2021. It connects major production regions with domestic markets and export ports, as shown in Figure 69. The system combines Logum's own pipelines with those operated by Petrobras, covering a total of 1,400 kilometres and offering an annual transport capacity of up to nine billion litres of ethanol (Logum, 2023).

FIGURE 69. Integrated pipeline logistics system for bioethanol

Source: Logum (2023).

The system's current operational terminals have a combined storage capacity of 617 million litres. In the same year, the volume of ethanol transported via the system reached 4.3 billion litres—an increase of 22% compared to the previous year (EPE, 2024b).

An assessment of the energy consumption and greenhouse gas (GHG) emissions associated with pipeline use, under operating conditions similar to those of the Logum system, was conducted by Leal Jr. and D'Agosto (2011). The case study examined the transport of bioethanol from a mill in Turvelândia, located in Goiás—a region that has seen major sugarcane expansion in the past decade—to Senador Canedo, also in Goiás, home to a Petrobras fuel terminal that supplies the Central-West region. From there, three logistics alternatives were considered for reaching the Port of São Sebastião in São Paulo state, a potential export hub—namely full road transport using 45 m³ lorry tankers, rail transport using 100 tanker trains (each with 103 m³ capacity), and pipelines (with a capacity of 33,000 m³/day). The main results are shown in Table 28, which details the distances involved and the energy and emissions performance of each transport mode.

TABLE 28. Energy consumption and GHG emissions for transporting bioethanol from Turvelândia, Goiás, to São Sebastião, São Paulo

MODE AND DISTANCE	ENERGY CONSUMPTION (MJ/1000 TONNE.KM)	GHG EMISSION (KG/1000 TONNE.KM)
Road, 1,065 km	1,663	119.0
Road, 234 km + Railroad, 1,197 km	658	46.7
Road, 234 km + Pipeline, 1,077 km	402	22.3

Source: Leal Jr. and D'Agosto (2011).

These results clearly highlight the benefits of pipeline transport in the scenario analysed. Compared to road and rail, pipeline transport reduces energy consumption by 60% and 39%, respectively, while lowering GHG emissions by 61% and 52%.

9.

Bioethanol for a FAIR energy transition: Fast, Accessible, Inclusive, and Renewable

Modern bioenergy is the overlooked giant of the renewable energy field. Its share in the world's total renewables consumption is about 50% today...
We expect modern bioenergy will continue to lead the field and has huge prospects for further growth.
But the right policies and rigorous sustainability regulations will be essential to meet its full potential.

Fatih Birol,
Executive Director, International Energy Agency (IEA),
October 2018.

Despite its evolution over more than a century, its established presence in many countries, and the favourable prospects for expanding production and use on a global scale, doubts and prejudices about bioethanol still persist in some contexts. It is essential to disseminate accurate information about this technology to guide informed decisions and accelerate its adoption at a pace consistent with the urgent demands of sustainable development.

Throughout this book, concrete facts and data have been presented regarding the efficient conversion of solar energy into a renewable fuel with significant potential for immediate production and application in the current global vehicle fleet, capable of promoting decarbonisation to a relevant extent in the transport of goods and people. In effect, there are no technological obstacles or natural limits, within a responsible environmental framework, that would prevent the widespread use of bioethanol. This biofuel should not be seen solely as a "transitional solution" to immediately and increasingly replace fossil fuels but also as an energy vector with considerable potential to meet a substantial share of future mobility demand in synergy with electricity.

To highlight the key messages of this book, this chapter summarises the conclusions of the previous chapters and reviews the challenges to be addressed and the recommendations for implementing bioethanol production and use programmes on a sound basis. In this regard, the importance of international cooperation is emphasised. By clarifying and offering real-world examples, it has contributed, and can further contribute, to promoting energy rationality through sustainable bioethanol in many countries.

9.1. Biothanol as fuel for a desirable future

The energy transition in mobility is crucial for reducing greenhouse gas emissions and combating climate change. Despite significant advancements in the adoption of renewable energy across various sectors, the transport sector remains heavily reliant on oil. This sector contributes approximately 30% of global energy consumption and a significant portion of CO_2 emissions. However, the energy transition in transport is more of an expectation than a reality due to the large fleet of gasoline-powered vehicles, the need for substantial investments in electrification infrastructure, and the dependence on strategic and scarce materials.

International energy agencies stress the need to increase the production and use of sustainable biofuels to achieve climate and energy security goals. The International Renewable Energy Agency (IRENA) projects that bioenergy could play a major role in limiting global temperature increases, with biofuels' contribution to transport expected to increase more than fourfold by 2050. The International Energy Agency (IEA) also calls for robust growth in biofuel consumption over the next five years to meet these objectives. Besides decarbonisation, implementing bioenergy promotes sustainability in a broad sense, improving social conditions and fostering global trade on a sound basis.

Bioethanol is a qualified vehicular fuel that has seen increasing global adoption due to its economic, environmental, and strategic advantages. Bioethanol is versatile and can be used efficiently in combustion engines and turbines, as well as being seamlessly integrated into existing logistics, storage, and distribution systems. It also enhances energy security by diversifying energy sources, reducing dependence on fuel imports and promoting domestic production. Many countries, including Brazil, the United States, and various European nations, blend bioethanol with gasoline or use it in pure form in flexible fuel vehicles (flex-fuel).

Bioethanol improves combustion efficiency and reduces pollutant emissions due to its high oxygen content and octane rating, making it a valuable additive and octane booster for gasoline. Moreover, the substantial reductions in specific emissions that can be achieved through the combination of its low carbon intensity with the high efficiency of modern engines, especially in bioelectric vehicles (*e.g.*, hybrid EVs fuelled by bioethanol), corroborate bioethanol as not only a short-term but also a long-term mitigation strategy. Further reductions in bioethanol carbon intensity are also expected with the progressive deployment of practices such as second-generation technologies, cane energy, biomethane from vinasse, and carbon capture and storage or utilisation.

Bioethanol can serve as a decarbonisation mechanism in various sectors. In addition to the significant potential for decarbonisation in road transportation, bioethanol can also be utilised in hard-to-abate sectors. It can be adopted as a platform for drop-in solutions, such as through the alcohol-to-jet (ATJ) pathway for producing sustainable aviation fuels (SAF). Furthermore, it can also be used as an alternative feedstock for plastics, among other chemical, as well as synergically integrated into hydrogen production and carbon capture and storage or utilisation.

There is vast potential to produce bioethanol with competitive sustainability indicators. Bioenergy contributes significantly to a fair energy transition, especially in tropical countries, where bioenergy has always played a prominent role. Modern bioenergy, covering around 12% of global energy consumption, is produced through efficient and environmentally friendly technologies. Brazil, for instance, uses sugarcane, maize, and other forms of bioenergy, which represented 67% of its renewable energy production in 2023, whilst using less than 10% of national agricultural land, with more than half of the country's territory excluded as protected or sensitive land.

The expansion of bioethanol using low carbon stock areas can lead to important environmental benefits. This approach reduces the environmental impact and supports biodiversity conservation. For example, the expansion of bioethanol in Brazil has been primarily based on using degraded pastures and existing agricultural lands, which has frequently led to higher carbon stocks in the soil while minimising indirect land use changes. Innovations like second crop maize bioethanol production further enhance sustainability by utilising existing agricultural cycles without additional land requirements. Other practices, such as proper residue management and integrated livestock-crop systems, also help to minimise negative impacts and maximise environmental benefits.

The socio-economic impacts of bioenergy production are advantageous compared to fossil fuels. Evidence from various studies shows that the bioenergy sector generates significantly more employment per unit of energy output than petroleum refining. This job creation is crucial for countries in the intertropical region, which have significant potential for modern bioenergy production and need to generate employment and income to support sustainable development.

Bioenergy production also promotes income distribution in favour of labour over capital, contributing to equitable economic development. The production of biofuels channels a larger share of gross domestic product (GDP) towards labour remuneration compared to fossil fuels. This redistribution of income supports broader economic development and social equity, particularly in regions with high bioenergy production potential.

Mechanisation in bioenergy production, especially in agriculture, has significantly transformed the sector. In Brazil, the mechanised harvesting of sugarcane has increased efficiency, reduced labour intensity, and minimised environmental impacts. While mechanisation reduces the total number of jobs, it increases the demand for skilled labour and offers better remuneration. This shift requires policies focused on worker requalification and education to ensure that the economic benefits of mechanisation are widely shared.

Bioenergy can drive domestic regional development, particularly in poorer regions, by generating employment and stimulating local economies. The biofuel production chain includes agricultural activities, processing, and distribution, creating direct and indirect jobs. Additionally, bioenergy infrastructure investments, such as roads and professional training, further support regional development. Social indicators such as life expectancy, infant mortality, and literacy rates improve with increased energy availability and income, contributing to overall development.

The production of biofuels complements food production. In Brazil, the evolution of biofuel production has not adversely affected food prices or availability. Instead, it highlights the potential for productivity gains and complementarities between biofuel and food production, among other coproducts. Public policies, such as those promoting integrated agriculture-forestry systems, support this synergy and enhance the sustainability of both sectors.

The environmental and socio-economic benefits of bioethanol make it strategic for achieving sustainable development goals. Robust policies, international collaboration, and continuous innovation are key to achieving the full potential of biofuels and ensuring a fair and inclusive energy transition. By promoting a fair energy transition that prioritises both environmental sustainability and socio-economic development, bioethanol (and bioenergy) can significantly contribute to a sustainable low-carbon future in different parts of the globe.

The economic competitiveness of bioethanol is higher than it seems. Distortions in the pricing of gasoline, often shaped by subsidies and lacking balanced taxation by useful energy content and incorporation of negative externalities, affect the consumer price of bioethanol. Policies like the Low Carbon Fuel Standard in California, United States, and RenovaBio in Brazil, which focus on incentivising low carbon intensity biofuels, are crucial for maintaining the competitiveness of bioethanol.

Bioethanol represents a successful business case. The technological maturity already achieved, along with promising prospects for further gains in productivity and efficiency across production and end-use processes—combined with the expansion of the global market—has attracted major corporations such as Shell and BP, key bioethanol producers in Brazil, as well as automakers like Toyota and Stellantis, which are developing and marketing high-performance vehicles powered by pure ethanol.

9.2. Overcoming challenges and implementing sustainable biofuels markets

As highlighted and explained in previous chapters of this book, there is a broad base of natural resources and robust technical conditions to increase the contribution of bioenergy, especially bioethanol, to the global energy matrix, with important benefits. However, the implementation of sustainable bioethanol markets requires adequate planning to overcome two main obstacles: the lack of correct information and the lack of an environment favourable enough to foster investments in bioethanol production systems.

Misinformation can occur due to simple ignorance or the lack of scientifically based information about the bioethanol production chain and its implications. However, it can also occur in much worse ways, due to the presence of false and prejudiced ideas (Tomei & Helliwell, 2016), often spread by economic interests that are contrary to the development of a sustainable biofuels market. In both cases, it is essential to inform properly the different audiences, from citizens, consumers, fuel, and vehicle market agents to media agents and the academic community. Today, there are excellent sources of sound technical and scientific studies on all aspects of bioethanol production and use, exploring correctly controversial topics such as land and water use, competition with food production, and impacts of bioethanol on combustion engines, etc. See, for example, a set of studies selected by the Bioenergy Research Program (BIOEN) of the São Paulo Research Foundation (FAPESP) (BIOEN/FAPESP, 2025).

To address the second obstacle, it is important to recognise that investments in agro-industrial bioethanol production systems are mainly private, in which economic risks are decisive factors in defining feasibility. In this context, the role of the government is crucial in coordinating government and private efforts. In addition to providing favourable conditions for investments via appropriate financing, it is equally important to reinforce the predictability of bioethanol demand. In this sense, the government can act through mandates for the compulsory addition of bioethanol, and by adopting tax regimes and pricing mechanisms that do not increase the typical risks that exist in the global energy market affecting fuels in general. With sufficiently assured demand and prices determined in a balanced manner within a stable legal framework, sustainable bioethanol markets have developed in several countries.

9.2.1. Promoting bioenergy investment and sustainability in Latin America: an IRENA perspective

> *This section is based on the conclusions and recommendations of a workshop that brought together stakeholders from biofuel markets in Latin America, promoted by the International Renewable Energy Agency (IRENA). Although focused primarily on this region, these reflections are useful for any developing country in similar conditions.*

Latin America's bioenergy potential has been only partially developed, with some countries boasting significant production bases and well-established markets, while others are only beginning exploration. Aiming to identify barriers and suggest strategies to promote investment and the development of sustainable bioenergy, a workshop was held in São Paulo in March 2023 with the participation of representatives of public and private institutions, and national and multilateral stakeholders in the region (IRENA, 2024c).

This workshop provided a rich debate among actors with diverse perspectives on how to attract investment in the bioenergy sector in the region. Key findings from the presentations and discussions in the workshop are presented as follows.

An adequate legal and regulatory framework is essential. Suitable biophysical conditions for biomass production and attractive economic development are not sufficient for promoting bioenergy production in the region. The bridge between this resource and its sustainable exploitation is provided by private companies and, at the same time, promoted and regulated at the governmental level. Therefore, it is essential to have a sustained, adequate, and stable legal and regulatory framework that defines and promotes, with sufficient certainty the evolution of the demand for biofuels and/or bioelectricity, and that allows their commercialisation under sufficiently attractive conditions, to minimise the financial risk in bioenergy investments.

Evaluating the economic worth of reducing greenhouse gas emissions through biofuels has proven to be a successful approach. The positive outcomes attained by the RenovaBio programme in Brazil over recent years serve as a compelling demonstration that assessing and assigning economic value to the mitigation of greenhouse gas emissions can yield significant benefits. The transparent and consistent methodology and modelling adopted in RenovaBio can be implemented in the region relatively quickly, with significant economic and environmental results, enabling compliance with national decarbonisation targets for the fuels used in the transport sector.

Cooperation among countries is important. In Latin America, countries that have developed significant bioenergy systems in their economies co-exist with countries with similar natural and historical conditions that are still trying to promote bioenergy, without managing to overcome the barriers, prejudices, and bottlenecks among the population and economic agents. Dialogue between governments, involving industry, financial institutions, and multilateral agencies, could improve the knowledge base and provide benchmarks for countries interested in promoting bioenergy to meet social and environmental demands, stimulating investment in bioenergy systems.

The issues above highlighted barriers and opportunities to be considered and explored to foster sustainable domestic biofuel markets in the region, especially in countries with incipient markets. Based on these core areas, the steps below were suggested, as priorities at country level, to progressively implement sustainable bioethanol markets.

1. **Defining an appropriate legal framework.** Considering the contexts observed in the energy transition in the region, the first necessary step is to establish a sustainable bioenergy law, with objectives consistent with local potential and conditions. This should consider an institutional basis with sufficient scope and autonomy to define, detail,

and implement strategies and policies to promote bioenergy. It must be capable of guaranteeing sustainability and overcoming the barriers to the investment needed to develop the production and use of biofuels and bioelectricity.

A possible general objective for a Sustainable Bioenergy Law that, albeit generic, covers the main drivers of sustainable bioenergy could be: To promote the sustainable production and use of bioenergy, in its different forms, that contribute to energy security, the reactivation of the agricultural sector, national socioeconomic development, and sustainable human development, particularly in rural areas, as well as improving air quality in cities and mitigating climate change.

2. **Implementing a bioenergy market.** An institutional structure must be introduced based on the legislation, defining how goals consistent with medium- and long-term strategies will be implemented and by whom. This must include comprehensive financial and fiscal incentives, including a balanced tax framework, in line with the mandates and obligations, recognising the externalities associated with biofuels and bioelectricity.

   This institutional structure should ideally establish provisions to support research and technological development, marketing and infrastructure, human resource training and capacity building, and conditions to provide reliable information services and improve public awareness, within a framework of action that strengthens the governance and sustainability of the bioenergy market.

3. **Progressively developing and diversifying products and markets.** Given the diversity of bioenergy technologies and biofuels, it is important to start by considering the implementation of bioenergy production and use systems, starting in markets that are considered limited, using low levels of blending. The use of ethanol/gasoline and biodiesel/diesel blends with up to 10% of properly specified biofuel (E10 and B10) is well proven in fuel logistics systems, with millions of vehicles worldwide on the road already using such blends. These blends can be adopted quickly in any region. Higher levels of blending would require prior market assessments or even adapting engines for the use of pure biofuels. Properly designed and enforced, biofuel markets can expand and consolidate steadily. This enables countries that have not yet embraced biofuels to gain confidence by looking at the experience

> of benchmark countries in the region. This highlights the opportunities for cooperation, to be mentioned in the next subsection.

Although advanced and promising technologies are maturing, their wide adoption is still incipient and, in most cases, in the middle of their learning curve. Currently, the conventional technologies for producing biofuels are efficient enough, competitive, and reliable, to be the first option of choice in young biofuel markets.

9.3. International cooperation for the promotion of sustainable biofuels

This section was prepared for this book by Laís de Souza Garcia, Pedro Tiê Candido Souza, and Otávio Forattini Lemos Igreja, from the Renewable Energy Division within the Department of Energy of the Brazilian Ministry of Foreign Affairs.

The transition to a sustainable low-carbon economy worldwide must be an inclusive process that considers the need for job creation, respects diversity, and contributes to social development, leaving no one behind. At the same time, it must be an opportunity for the development of new industries through technological innovations and investment attraction. Creating these opportunities, particularly in developing countries, will contribute to the reduction of global inequalities by potentially reshaping global value chains and the international flow of financial resources.

From this perspective, the production and use of sustainable biofuels can represent a major contribution from the Global South to global energy transitions. Biofuels, the resources most abundant in developing countries, can be a competitive, convenient, and technologically mature option to immediately reduce emissions in hard-to-abate sectors, such as transport and industry, while generating sustainable jobs and contributing to reduce the demand for fossil fuels, as demonstrated by the Brazilian energy sector's decades-long experience.

International cooperation—be it bilateral, regional, or multilateral—is a key tool for reaching the full potential of sustainable biofuels in global decarbonisation efforts and disseminating the benefits they can generate to nations and local communities. Through cooperation, countries can learn from each other's experiences and best practices in a horizontal, coordinated, and integrated manner, stimulating innovation and paving the way for a wider array of possibilities in the energy field. Cooperation between countries promotes improvement in regulation, public policy, production, efficiency, and sustainability, thereby contributing to growing and stable biofuel markets, both domestically and internationally.

As no country is the same as another, and each experience must be adapted to suit its respective reality, substantial dialogue between experts, legislators, regulators, and industry representatives is the best way for countries to learn from each other's successes and mistakes and find solutions to promote sustainability in the energy sector.

9.3.1. Brazilian initiatives to promote sustainable bioenergy abroad

With the latter in mind, Brazilian diplomacy stands out in promoting bioenergy. This perspective has been one of the main axes of Brazilian energy diplomacy since the beginning of this century. Starting a phase of active presidential diplomacy and engagement in bilateral, regional, and multilateral promotion of ethanol, Brazil established an Department of Energy within its Ministry of Foreign Affairs in 2006. In the three years that followed, the country signed approximately 30 bilateral memoranda of understanding and cooperation on bioenergy, mostly with African countries, but also including a cooperation instrument with the United States in 2007.

During this phase, the G8+5 (Brazil, China, India, Mexico, and South Africa) agreed to launch a Global Bioenergy Partnership "to support wider, cost effective, biomass and biofuels deployment, particularly in developing countries where biomass use is prevalent," through the July 2005 Gleneagles Plan of Action (UK, 2005). This led to the establishment of the Global Bioenergy Partnership (GBEP), launched in 2006 and now hosted at the Food and Agriculture Organization of the United Nations (FAO). Following its objectives of fostering the sustainable development of bioenergy, establishing a harmonised methodology to measure GHG emission reductions from biofuels and solid biomass use, and promoting awareness and information exchange on bioenergy, the GBEP now includes 39 Partners (23 national governments and 16 organisations) and 51 Observers (33 national governments and 18 organisations).

In the face of unfounded attacks against biofuels based on biased sustainability criteria and the "food versus fuels" dilemma, efforts rose in the multilateral arena, given the sense of urgency prompted by the Paris Agreement and the world's renewed impetus to reduce emissions. In 2016, Brazil created the Biofuture Platform, which it led for the following five years. The initiative is dedicated to fundamental topics related to the expansion of sustainable bioenergy production and use globally. The Biofuture Platform is a noteworthy example of how country-led initiatives can expand their outreach as the biofuels market is further consolidated and demand rises in the context of an unprecedented climate urgency.

The originally Brazilian-led project was turned into an initiative of the Clean Energy Ministerial (CEM) and chaired by the US since 2021, supported by leading countries Argentina, Australia, Brazil, Canada, India, and the Netherlands. One of its outcomes was the CEM Biofuture Campaign, which sought to enable the reduction of GHG emissions and foster a circular economy by showcasing pathways by which countries, companies, and consumers can substitute sustainable bio- and waste-based Fuels, Chemicals, and Materials for their fossil equivalents. In 2024, the Biofuture Campaign was essential for the Turin Joint Statement on Sustainable Biofuels, in the context of Italy's G7 Presidency, which joined more than 80 signatories. Additionally, the Campaign created a leaders' coalition of associations and companies across the world. It has now become the Biofuture Industry Council, with the objective of fostering government-industry joint work-streams and advising the CEM Biofuture Platform, the International Energy Agency (IEA), and the CEM, among other international organisations and initiatives.

In recent years, the Brazilian Ministry of Foreign Affairs, the Brazilian Sugarcane and Bioenergy Industry Association (UNICA), and the Brazil Ethanol Cluster (APLA), supported by the Brazilian Trade and Investment Promotion Agency (ApexBrasil), joined forces to put in place a programme called "Sustainable Mobility: Ethanol Talks." The Ethanol Talks roadshow was taken to India (twice, in 2020 and 2021), Pakistan (2020), Thailand (2020), Argentina (2022), Guatemala (2022), Costa Rica (2023), Indonesia (2023), and Vietnam (2024).

The aim of the programme is to visit countries with potential in the sugarcane agroindustry to display the benefits of ethanol for sustainable mobility, with particular emphasis on the need to adapt experiences according to local realities. Ethanol Talks also aims to promote rich, profound, and substantial dialogue between experts, policy makers, regulators, and sector representatives from Brazil and the host country. Such a programme stimulates dialogue that fosters the exchange of experiences and contributes to identifying avenues for cooperation in the development and/or strengthening of the ethanol industry globally.

India is a vital example of the positive impact of Ethanol Talks. The seminars and the intense bilateral cooperation that followed with Brazil helped boost the production and use of biofuels in India, as well as the dissemination of flex-fuel vehicles across the country, with the objective of reducing emissions from the transportation sector. As a result, the progressive blend of ethanol into gasoline in India is set to reach 20% in 2025. The Indian experience opened doors and paved the way to encourage the production and use of biofuels in other developing countries, especially in Southern and Southeast Asia.

On the multilateral level, the Global Biofuels Alliance (GBA), launched by India during its G20 Presidency in 2023, is a fundamental organisation to create and expand biofuel markets in the Global South. The initiative now unites 32 countries and 14 international organisations and contributes to fulfilling the IEA's recommendation to triple the production of liquid biofuels by 2030 as a fundamental step towards carbon neutrality in 2050. The GBA aims to accelerate the global uptake of biofuels by facilitating capacity-building exercises across the biofuel value chain, providing technical support for national biofuel programmes, promoting the sharing of policy lessons and technological advancements, and encouraging the utilisation of sustainable biofuels through the participation of diverse stakeholders. It intends to act as a knowledge and expert hub, serving as a catalytic platform to foster global collaboration for the advancement and widespread adoption of biofuels. The GBA aims to make a significant impact by accelerating biofuel adoption in countries with existing biofuel targets and encouraging countries without biofuel targets to adopt biofuels. Supported by a multi-stakeholder approach, the alliance aims to ensure comprehensive and inclusive progress in the biofuels sector.

In 2024, it was Brazil's turn to preside over the G20, which includes the Energy Transitions Working Group (ETWG). The activities of this working group have earned more attention since COP28 in Dubai, when countries made new commitments for the increase of renewable energy and energy efficiency, as well as for the reduction of dependence on fossil fuels. In this context, the Brazilian Presidency established three priority areas for the ETWG: (i) Accelerating financing for energy transitions, especially in developing countries; (ii) Social dimension of energy transitions; and (iii) Innovative perspectives for sustainable fuels.

As a result of these efforts, the G20 approved two consensual documents in 2024 recognising the role of biofuels. The G20 Energy Transitions Ministerial Outcome Statement encouraged consistency, mutual recognition, transparency, and interoperability across methodological approaches for assessing GHG emissions of sustainable fuels, contributing to their scalability, affordability, fair competition, and rapid deployment. The G20 Rio de Janeiro Leaders' Declaration underscored the crucial role of technologically neutral, integrated, and inclusive approaches to develop and deploy a variety of low-emitting energies, sustainable fuels and technologies, and encourages the use of mutually recognised methodologies and standards for assessing greenhouse gas emissions.

In support of the Brazilian G20 Presidency, the IEA launched the reports on carbon accounting for sustainable biofuels and towards common criteria for sustainable fuels, which recognise the important role of sustainable biofuels in decarbonising the energy sector and explore the feasibility and implications of setting up common criteria to enable fair comparisons of sustainable fuels.

This year, the BRICS countries, which account for nearly half of total global energy output, held incisive discussions on sustainable fuels. For the BRICS Committee of Senior Energy Officials, the Brazilian chairpersonship invited member countries to collaborate on a BRICS Report on New and Sustainable Fuels, focusing on policies being developed within each of the BRICS countries. The initiative was provoked by the need to urgently increase production and deployment of sustainable fuels as important decarbonisation alternatives for developing countries, while supporting energy security, affordability and sustainability. The BRICS countries collaborated to identify bottlenecks in the production and use of those fuels and to find solutions and recommendations to speed up and scale their production. This involved recognising the distinct realities of different parts of the world, and where each new technology may work best.

There is endless potential for international cooperation in the promotion of sustainable biofuels. The biofuels market is unavoidable for the achievement of global net-zero emission targets, as a viable, immediate, and complementary solution. It is up to international actors and stakeholders to develop regulations, seek standards harmonisation, and foment coordination to improve efficiency, production, and innovation in this field, and accelerate decarbonisation in hard-to-abate sectors. International cooperation is the only path to achieve this and has already shown significant results towards this common goal of interest to all.

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