TECHNICAL NOTE N° 5

AN INTRODUCTION TO THE BIOFUEL SECTOR IN LATIN AMERICA AND THE CARIBBEAN

The role of Biofuels in the decarbonization of the energy matrix

Energy Join us

This document was prepared under the guidance of

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GLOSSARY

LCA	Life Cycle Assessment
LAC	Latin America and the Caribbean
ANP	Agencia Nacional del Petróleo, Gas Natural y Biocombustibles de Brasil
ASTM	American Society for Testing and Materials
AtJ	Alcohol-to-Jet
NBDES	National Bank for Economic and Social Development
CCS	Carbon Capture and storage
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
FOGs	Fats, Oils, and Greases // Grasas, Aceites y Sebos
FT	Fischer – Tropsch process
GHG	Greenhouse gases
gCO_2eq/MJ	Grams of Carbon Dioxide equivalent per Megajoule
HEFA	Hydroprocessed Esters and Fatty Acids // Esteres Hidroprocesados y Ácidos Grasos
HVO	Hydrotreated Vegetable Oil // Aceite Vegetal Hidrotratado
IATA	International Air Transport Association.
ISCC	International Sustainability and Carbon Certification
NO_x	Nitrogen oxide
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
PNDV	National Green Diesel Program // Programa Nacional de Diésel Verde
ProBioQAV	National Sustainable Aviation Fuel Program // Programa Nacional de Combustible Sostenible para la Aviación
PtL	Power-to-Liquid
RSB	Roundtable on Sustainable Biomaterials // Mesa Redonda sobre Biomateriales
SAF	Sustainable Aviation Fuel

1. INTRODUCTION

The energy transition towards a sustainable future requires the incorporation of renewable and low-emission alternatives that gradually replace fossil fuels. In this context, Latin America and the Caribbean (LAC) is in a strategic position to lead this transformation due to its abundant natural resource potential, the technical quality of its human resources, and a consolidated experience in the agricultural sector.

Within the regional context, low-carbon biofuels represent a key solution for the decarbonization of critical sectors such as land, air, and maritime transport where dependence on fossil fuels remains high. Produced from diverse biomass —such as sugarcane, maize, palm, as well as agricultural and forestry residues— these fuels offer a substantial reduction in net carbon emissions when assessed through a comprehensive life-cycle approach.

Their compatibility with existing energy and transport infrastructure —without the need for significant modifications to engines or distribution systems— position biofuels as a viable and immediate alternative in the fight against climate change. Furthermore, its production generates significant environmental and socio-economic benefits: it fosters rural development, generates employment, invigorates the agricultural economy and promotes technological innovation, thereby granting the region unique competitive advantages.

In 2023, global production of liquid biofuels reached 180,544 thousand m^3 (IICA, 2024), of which LAC contributed 27% with 47,827 thousand m^3. Brazil led regional production by a wide margin, representing nearly 25% of global production and 93% of total production within LAC (SieLAC, 2024). In the region, bioethanol and biodiesel accounted for 81% and 19% of liquid biofuel production, respectively, with an estimated domestic consumption of 69 liters per capita in 2023.

Despite notable progress, the implementation of biofuels in LAC faces several challenges. Factors such as the low energy density of biomass, geographical dispersion of resources, competition for land use, and the lack of robust public policies limit the full realization of its potential. Likewise, sectors difficult to decarbonize, such as air and maritime transport, demand advanced and innovative technologies, which in turn require greater investment and international cooperation.

Looking ahead, achieving carbon neutrality in the energy sector by 2050 will require a substantial increase in regional production of liquid biofuels.

It is estimated that production will need to increase by approximately 360% compared to 2023 levels, which would imply almost quadrupling current production to reach 172,990 thousand m^3 in LAC

This technical note analyzes the current state of low-carbon biofuels in Latin America and the Caribbean, identifying key opportunities and challenges to enhance their contribution to the energy transition. The objective is to position biofuels as a sustainable, competitive, and essential instrument in both regional and global efforts to mitigate climate change.

2. CONCEPTUAL FRAMEWORK AND CURRENT PERSPECTIVE

2.1. Definition and characterization of biofuels

Biofuels are fuels derived from organic matter obtained from several sources such as agricultural crops, their residues and by-products, forestry and livestock activities, urban and industrial waste, as well as from the interaction of plant species such as algae and microorganism. As they originate from biological sources —and in many cases, from by-products of agricultural and industrials processes— biofuels represent an alternative to fossil fuels, potentially contributing to the reduction of net greenhouse gas emissions and the diversification of the energy matrix. However, the production must be managed sustainably in order to avoid adverse impacts, such as competence with food security, degradation or changes in land use of ecosystem interest, and deforestation.

The conversion of biomass into energy is achieved through chemical, physical and biological processes. Among the most common methods are **fermentation**, **transesterification**, **gasification** and **anaerobic digestion**. These technologies have evolved over time, allowing the development of several generations of biofuels —each with specific characteristic, advantages and challenges.

Biofuels can be classified according to several criteria, among which four are particularly prominent: their origin, nature, type and technological roadmap.

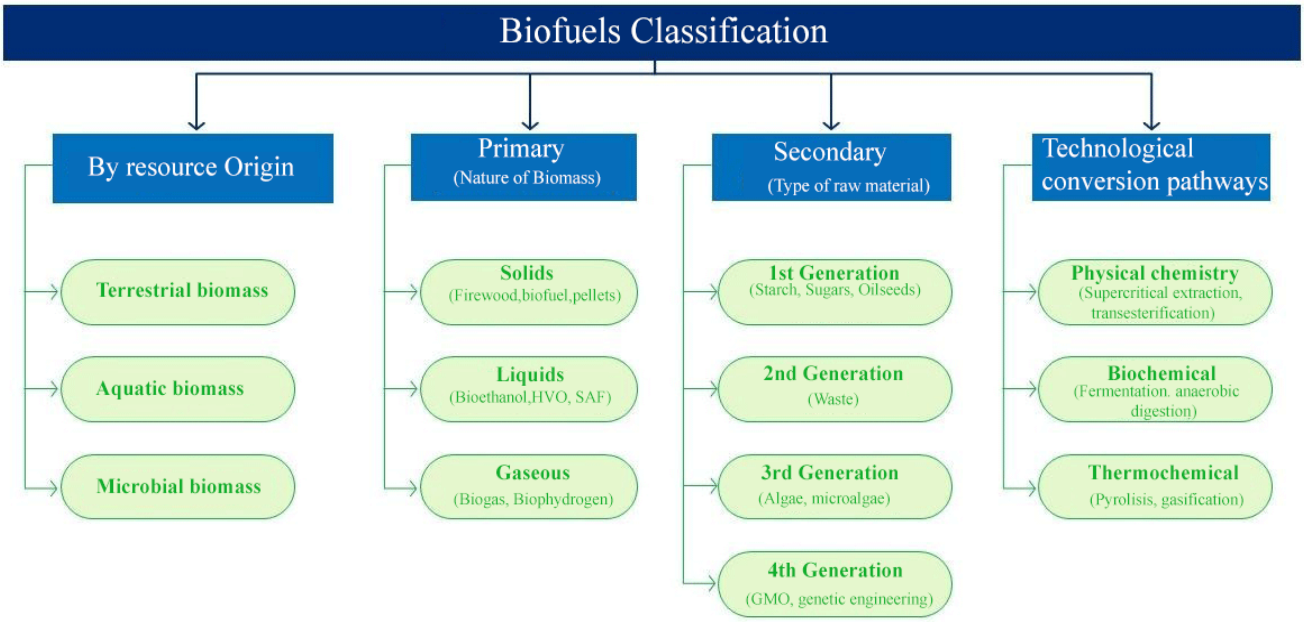
Figure 1 - Biofuels classification criteria

CRITERIA	CLASSIFICATION
ORIGIN	Classification according to the organic origin of the resource
NATURE	Classification according to the status of the resource
TYPE	Differentiation between the type of organic matter, food and non-food resources
TECHNOLOGICAL ROADMAP	Consideration based on the processes to transform biomass into energy

Source: Own elaboration

The following figure graphically illustrates the categorization of biofuels

Figure 2 - Biofuels classification scheme



Source: Jiménez, M & Castillo, A. (2021)[1].

Historically, advances in technology have led to the development of new processes and new generations of biofuels. The table below briefly describes the raw materials and processes associated to each of the **four generation of biofuels**, highlighting key differences in biomass source and the conversion methods used to obtain the fuel.

Figure 3 - Biofuels classification by generations

GEN.	RAW MATERIAL	PROCESS
I	Food and oilseed crops (maze, sugarcane, soybean, palm oil)	**Fermentation**: bioethanol production. **Transesterification**: Biodiesel production.
II	Lignocellulosic waste (bagasse, straw, pruning residues and other non-food by-products)	**Enzymatic hydrolysis: C**onversion of biomass into fermentable sugars. **Gasification:** Transformation of biomass into syngas.
III	Algae and microalgae (fast-growing organisms cultivated in environments not suitable for conventional agriculture)	**Lipid extraction:** For biodiesel production by transesterification **Fermentation and other biochemical methods:** conversion into bioethanol and other fuels
IV	Advanced biotechnology systems (genetically modified organisms or integrated systems that combine diverse biomass sources)	**Advances biotechnological processes:** These include techniques for the production of fuels along with the capture and storage of CO_2. **Emerging technologies:** Integration of conventional methods with innovations in genetic engineering and bioprocesses.

source: Own elaboration based on: Scielo (2021) and Springer Link (2022).

[1] http://www.scielo.org.pe/scielo.php?pid=S2077-99172021000200265&script=sci_arttext&tlng=en

2.2. Low-carbon biofuels

Low-carbon biofuels are liquid or gaseous energy sources that over their entire life cycle, emit significantly lower amounts of CO_2 compared to conventional fossil fuels.

The reduction of GHG emissions is achieved through an approach that combines the **selection of sustainable raw materials** and the **optimization of biomass to energy technologies**. This entails the use of agricultural, forestry or non-food crop residues, as well as the enhancement of first-generation biofuel production processes —such as bioethanol and biodiesel— through **more efficient agricultural practices, reduced reliance on fossil inputs, and advances in carbon capture**. In this way, both advanced and first-generation biofuels can contribute in the decarbonization of the energy sector.

It is important to consider that the concept of low-carbon fuels is defined within a regulatory context that varies by country or market. In the United States, the Renewable Fuel Standard (RFS) classifies biofuel into four categories:

- Conventional,
- Advanced,
- Diesel from biomass, and
- Cellulosic.

According to this regulation, advanced biofuels and biomass diesel must reduce Greenhouse Gases (GHG) emissions by 50% over their life cycle, while cellulosic biofuels must achieve 60% reduction. In contrast, conventional fuels —such as maize based ethanol— are only required a 20% reduction. Importantly, once these thresholds are exceeded, no additional credits are awarded for higher improvements in carbon intensity.

In the case of Europe, regulatory limits have evolved over time, establishing increased requirements for emission reductions. Currently, the minimum threshold mandates a 65% reduction in emissions compared to a liquid fossil reference (valued at 94 gCO_2eq/MJ). While this approach incentivizes producers to meet and —in some cases, exceed— the minimum requirement in order to obtain market benefits, it does not necessarily provide additional rewards for achieving further reductions in carbon intensity.

Brazil, on the other hand, implements the RenovaBio program, established in 2017 through Law No. 13.576. This initiative promotes the production and use of biofuels based on their environmental performance. To achieve this, the program adopts a life-cycle assessment approach to certify GHG emissions of fuel expressed in terms of carbon intensity (gCO_2eq/MJ). Certified producers and distributors receive Decarbonization Credits (CBIO), which are traded in the market and enable companies to meet annual emission reduction goals. This system directly incentivizes actors who achieves ambitious improvements in emissions reductions, in contrast from the approaches adopted in the United States and Europe.

2.3. Integral analysis of the carbon footprint on biofuels

The carbon footprint of biofuels is a critical factor in assessing their climate impact and their contribution to the net reduction of GHG emissions. Traditionally, this assessment has relied on the **Life Cycle Assessment (LCA)** methodology, which focuses on identifying and quantifying emissions in each of the **four stages**:

1. **Biomass production:**
   Emissions resulting from agricultural activities, including planting, cultivation, harvesting, and land management are considered. It also considers the impact of land use changes, which may contribute to either carbon capture or release.
2. **Processing and Conversion:**
   The efficiency of the processes used to transform biomass into biofuels is evaluated, incorporating both the energy consumption and the emissions associated to the conversion process.
3. **Transportation and Distribution:**
   Emissions generated by the transport of raw material and the final product are quantified, which may fluctuate according to the infrastructure and distances involved.
4. **End use and combustion:**
   The direct emissions that occur during the combustion of biofuel are analyzed in comparison to those of conventional fossil fuels.

Although LCA has been fundamental in establishing a reference framework, it presents certain limitations, these include the complexity of data collection, regional variability in agricultural management practices, and challenges in dynamically incorporating technological advances, particularly in carbon capture and storage (CCS). Limitations of LCA are described in greater detail below.

- **Data Complexity and Regional Variability:**
  LCA accuracy relies heavily on the quality and consistency of the data used in each stage. Regional variations in agricultural practices, industrial processes, and changes in land-use can introduce significant uncertainties

- **Outdated responsiveness to Technological Innovation:** Traditional LCA Methodologies are often based on historical data and assumptions that may become outdated in the face of rapidly technologies evolution. For example, advances in carbon capture and storage (CCS) technologies and highly efficient conversion processes are not always adequately reflected in current assessments.

- **Technological adoption and adaptation:**
  The successful transfer of technology requires adaptation to the specific local context in which it will be implemented. This ensures both the appropriation by users and the efficient and sustainable performance of the solutions implemented.

- **Land Use Change Assessment:**
  Estimating the impact of land conversion (e.g. deforestation or agricultural land conversion) is particularly complex highly dependent on both geographical and temporal context.

To address these limitation, more dynamic and upgradable approaches have been developed to enhance the comprehensive carbon footprint assessments:

Dynamic and Upgradeable LCA:

The integration of real-time data through sensor. Satellite monitoring, and geographic information (GIS) enables the capture of variations in agricultural practices and process efficiency. This approach reduces the uncertainty associated with historical and regional data.

CCS Technology Integration:

Modern LCA models incorporate dedicated analyses of CCS technologies used in processing facilities. This enables the evaluation of not only generated emissions, but also the CO_2 captured and stored, providing a more accurate perspective of net footprint.

Simulation Models and Innovation Scenarios:

The use of simulation models that incorporate diverse technological and management scenarios enables to explore alternative pathways for emission reduction. These models are essential for forecasting the impact of future innovations and play a critical role in guiding energy policy decision-making.

Integrated Approaches to Carbon Accounting:

Recent studies propose integrated frameworks that combine LCA with risk analysis and economic evaluation. These frameworks go beyond assessing environmental benefits by also considering financial viability and the barriers to implement new technologies. As a result, they offer a holistic perspective on biofuels performance.

The assessment and management of carbon emissions in the life cycle of biofuels requires a holistic and dynamic approach that extends beyond traditional LCA methodologies. Integrating real-time data, capture and storage technologies, and the development of advanced simulation models are essential to overcome current limitations. These approaches enable more accurate and up-to-date evaluations of carbon footprint, supporting informed decision-making in the development and implementation of truly sustainable biofuels. By adopting these methodologies, the climate change mitigation potential of biofuels can be maximized, contributing meaningfully to the transition to a low-emission energy system.

2.4 Comparison of alternatives to reduce emission in transport

Biofuels have emerged as a key instrument for the decarbonatization of the transport sector, one of the largest sources of greenhouse gases (GHG) emissions worldwide. The urgent need to reduce these emissions has driven the development and adoption of complementary technologies and strategies, including electric vehicles, hydrogen-based fuels and energy efficiency measures.

The following table compares key aspects of alternatives to reduce emissions in the transport sector with a particular focus on the context of Latin America and the Caribbean.

Figura 4 – Alternatives to reduce emission in transport

Aspect	Biofuels	Electric Vehicles/Hybrids	Hydrogen and Synthetic Fuels (E-fuels)	Energy Efficiency
Definition and Sources	Biological sources: agricultural waste, forestry, non-food crops, etc.	Operate on electric power (EV) or combine electric and combustion engines (hybrids).	Use of hydrogen (for fuel cells) and production of synthetic fuels through electrolysis and CO_2 capture $_2$.	Improvements in engine technology, aerodynamics and logistics management without changing the energy source.
Lyfe Cycle Assessment	Considers all stages: biomass production, processing, transport and combustion; it includes impacts from land-use change and the integration of residual emissions, using technologies such as CCS.	Depends on the source of electricity (energy matrix) and the life cycle of the batteries (production, use and recycling).	It assesses the efficiency in the production of green hydrogen and the integration of capture and storage technologies	It focuses on reducing energy consumption during operation, without modifying the primary energy source.
Advantages	Take advantage of local resources, integration with existing infrastructure, generate income in rural areas, strength security and energy sovereignty	Zero direct emissions during operation, high energy efficiency, improvement in urban air quality and noise reduction	Near-zero emissions potential if renewable electricity is used, suitable for heavy transport applications and adaptable to existing infrastructure	Low investment, fast implementation and immediate reduction of fuel consumption.
Limitations	Risk of competition with food security and deforestation of ecologically important areas, variability in raw material availability and quality, and challenges in effectively integrating CCS.	Require a robust charging infrastructure and face limitations in hard-to-reach areas. It generates environmental and social impact associated with the production and disposal of batteries and depends on advanced technology and specialized supply chains.	High production costs, limited infrastructure for storage and distribution, and lower efficiency compared to other alternatives	Limited scope in terms of absolute emission reductions and need for continuous technological improvements in vehicle efficiency
Economic aspects and Infrastructure	Potential favorable return on investment in areas with an abundance of raw materials, but depends on public policies and subsidies to encourage sustainable production	High investment in charging infrastructure and battery management systems; it requires incentives and a clean electricity matrix to maximize benefits	Needs significant investments in technology and hydrogen distribution networks; with medium-long term potential in mature markets.	Lower initial investment and rapid implementation, being a complementary strategy that enhances other technologies without requiring structural changes.
Regional Factors in LAC	High availability of agricultural residues and by-products, diversity in soil management practices, and variability in local data that affect assessment accuracy	Advantages in urban areas with growing renewable capacity, but limited in regions with insufficient electricity infrastructure	Significant potential in countries with access to renewable energies and innovation policies, although it requires consolidating investments in R&D.	Easy to implement in various contexts, functioning as an immediate and complementary measure for the reduction of emissions.

Source: Own elaboration

The comparison of emission reduction alternatives in the transport sector reveals that, while each technology presents specifics advantages and challenges, a strategic combination of these solutions can significantly enhance efforts to mitigate climate challenge. Expected advances in hydrogen production, battery technologies and optimization in biomass processes will contribute to increase the efficiency of each alternative.

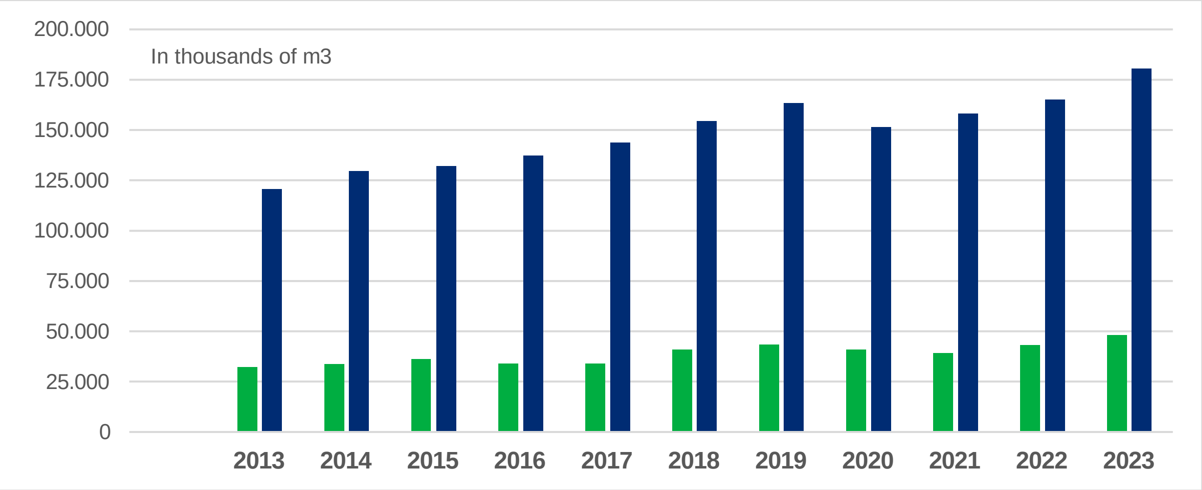
In this context, while electrification is emerging as the leading option for light and urban transport, hydrogen is expected to play a relevant role in industrial sectors. In Latin America and the Caribbean, liquid fuels stand out as a viable and promising alternative. Their ability to leverage abundant local waste and by-products, integrate into existing infrastructure, and promote rural development and technological innovation positions them as a strategic instrument for the decarbonization of heavy road transport, aviation, and river transport.

3. CURRENT STATUS OF BIOETHANOL AND BIODIESEL EN IN LAC

3.1. Evolution over 2013-2023

Over the past decade, Latin America and the Caribbean has established itself as a key player in the global biofuel market, contributing over a quarter of global production (OLADE 2024). In 2023, LAC's participation on biofuel production reached a 27%. Both LAC and the global market have experienced a **cumulative growth of 50%** in biofuel production over this period, reflecting parallel and sustained development in the region.

Figure 5 - Global and regional production of biofuels

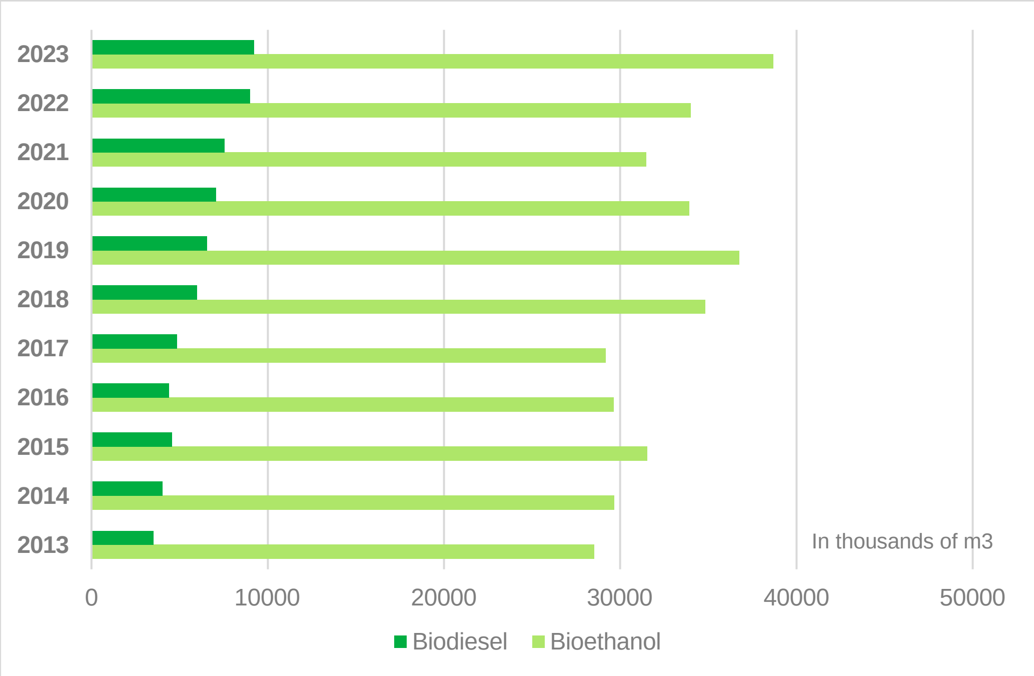


Source: SieLAC, IICA (2024)

Latin America maintains a diversified production of biofuels, highlighting bioethanol —derived mainly from the fermentation of sugars from sugarcane and maize— and biodiesel, produced from vegetable oils such as soybeans, sunflower and palm oil.

Figure 6 presents the evolution of bioethanol and biodiesel production in Latin America and the Caribbean over the last decade.

Figure 6 - Evolution of biofuels production in LAC



Source: SieLAC for LAC between 2013-2023

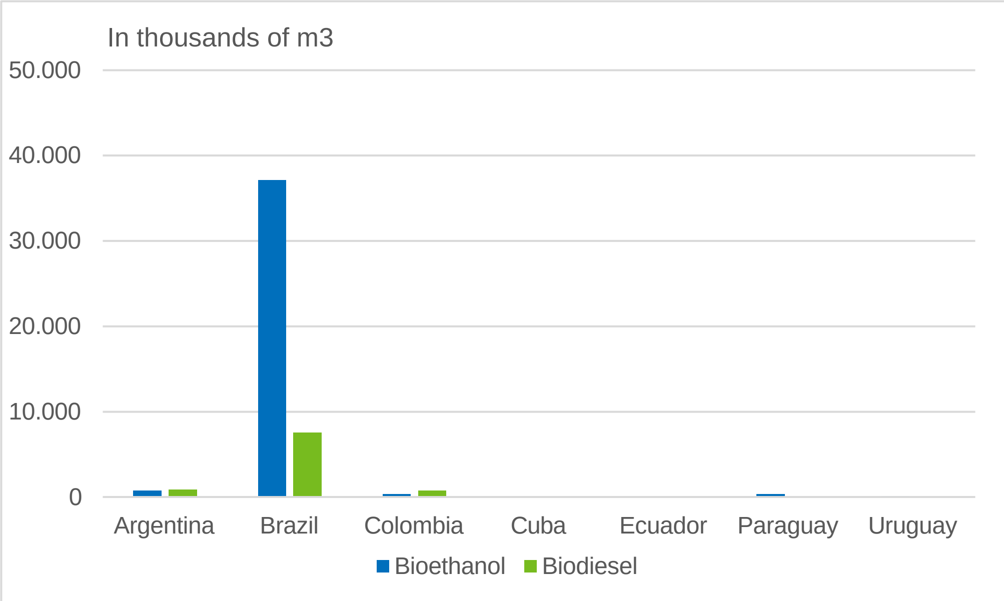
As observed, both biofuels have exhibited a general upward trend over the past decade. Although bioethanol production has historically surpassed that of biodiesel, an analysis of evolution over time reveals a significantly higher percentage growth in biodiesel production. **Biodiesel** has experienced a cumulative increase of **163%** in the period analyzed, while bioethanol has registered a growth of 36%. These figures reflect a greater dynamization on biodiesel production, potentially driven by factors such as the diversification of raw material sources and specific promotion policies for this type of biofuel.

3.2. Actual situation

Brazil is the leading biofuel producer in the region, 96% of bioethanol production and 82% of biodiesel production.

Currently, seven countries produce bioethanol in LAC, while five countries are involved in biodiesel production

Figure 7 - Biofuel production by country



Source: SieLAC for 2023

3.3. Public Policies & Regulations

The production and consumption of biofuels are closely tied to public policies and regulations that encourage their adoption. At both global and regional levels, several key measures have been implemented, among which the following are particularly noteworthy:

- **Support for Research, Development and Innovation (R&D&I):**
  Governments and international organization have supported R&D programs to improve technologies for production, conversion and optimization of biofuels. These initiatives include grants, investment funds, and collaborative programs between academic institutions, research centers, and industry, with the objective of enhancing efficiency and reducing costs.
- **Tax Incentives and Subsidies:**
  Tax exemptions, reductions or direct subsidies are offered to the production and consumption of biofuels. These measures aim to lower production costs and enhance their competitiveness against fossil fuels.
- **Blending Mandates:**
  Several countries have stablished mandates requiring the inclusion of a minimum percentage of biofuels in fossil fuels.

- **Carbon Credits and Financing Mechanisms:**
  Including biofuels in carbon credits schemes enables producers to generate additional income by demonstrating reductions in their carbon footprint. Moreover, dedicated financing lines—both nationally and internationally— have been stablished to support sustainable biofuel projects, sometimes through public-private partnerships.
- **Sustainability and Certification Regulations:**
  Standards and certifications have been developed to ensure the sustainable production of biofuels. These regulations require environmental impact assessments —such as Life Cycle Assessment (LCA) — and responsible biomass management measures. Their objective is to safeguard environmental benefits from practices that could drive deforestation or competition with food production.
- **Energy Transition Policies and National Strategies:**
  Several countries have incorporated biofuels into their national energy transition plans and strategies. These policies stablish emission reduction targets and promote the use of renewable energies, creating a regulatory framework that supports investment and the development of biofuel infrastructure.

Among these measures, **blending mandates** have demonstrated the greatest diffusion and impact. By setting minimum quotas, these regulatory instruments ensure a secure market for biofuels, thereby encouraging investment and facilitates the expansion of the infrastructure needed for their production and distribution

The table below summarizes the regulatory frameworks adopted by countries in the region and their current biofuel blending percentages.

(**Note**: For further details, refer to Annex 3.)

Figure 8 - Regulatory frameworks and biofuel blending rates

COUNTRY	ETHANOL	DIESEL	LAW
Argentina	12%	7,5%	27.640 / 2021
Bolivia	25%	25%	Supreme Decree 5.135 /2024
Brazil	27%	14%	8.723 / 1993 y 11.097 / 2005
Chile	N/A	5%	20.257 / 2008
Colombia	10%	10%	Resolution 40447 de 2022
Costa Rica	7%	N/A	36.447 – MINAE
Ecuador	5%	5%	Biofuels Promotion Law
El Salvador	10%	N/A	Bios Promotion 2011
Guatemala	5%	N/A	Bios Promotion 2008 + AG-159-2023
Jamaica	10%	N/A	National Ethanol Program 2008
Mexico	10%[2]	N/A	Biofuels Promotion 2008
Panamá	5%	N/A	42 / 2011
Paraguay	30%	5%	2.748 / 2005
Perú	7,8%	5%	28.054 / 2003
Dominican Republic	15%	N/A	57-07
Uruguay	8,5%	N/A	18.195 / 2007 y 2022

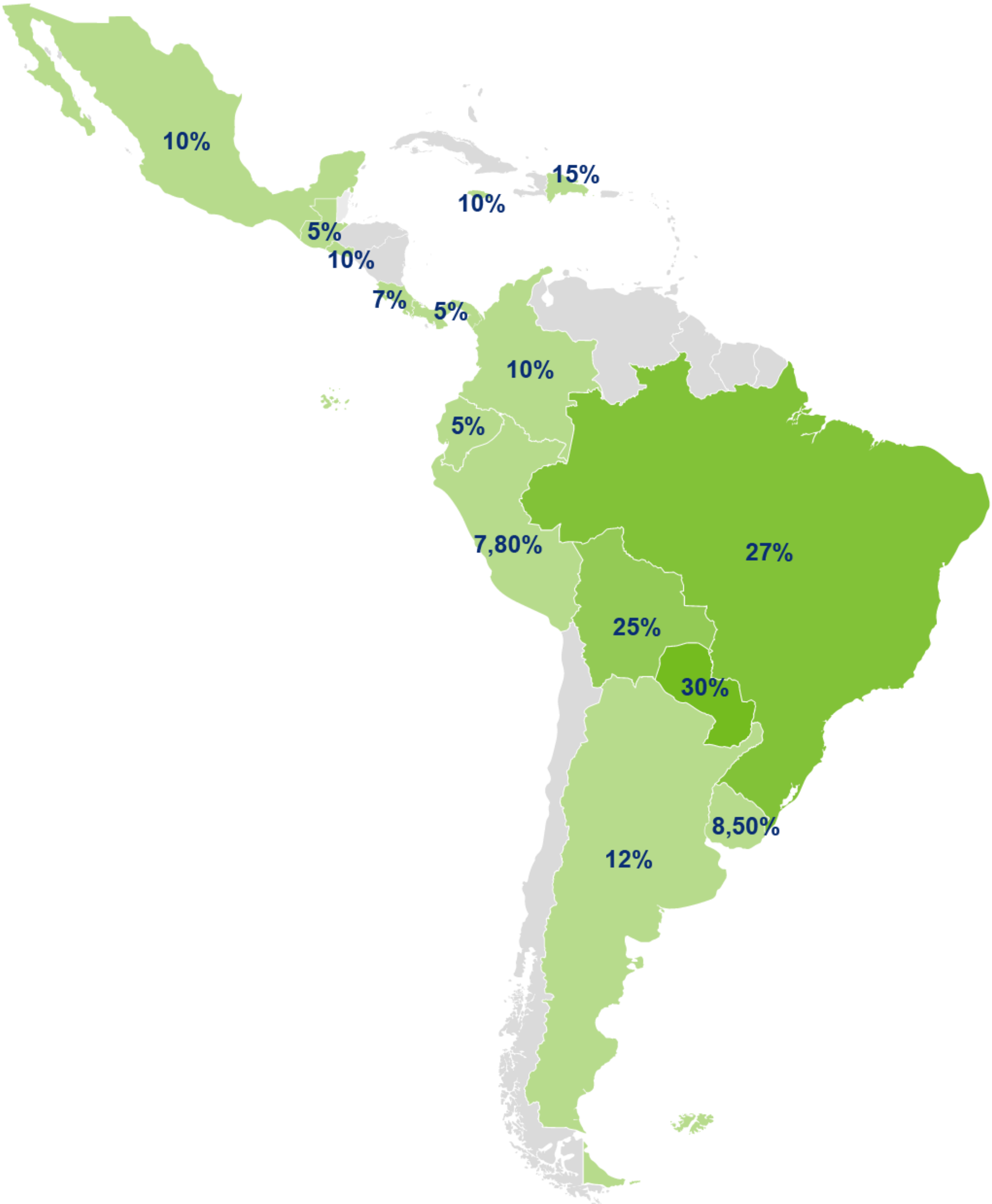
Source: Own elaboration (LAC 2024)

Note: The **i**nformation presented reflects the regulatory frameworks and data available as of the update date (2024).

Note: Blending percentages may vary based on regulatory updates and market conditions official sources should be consulted for the most current information.

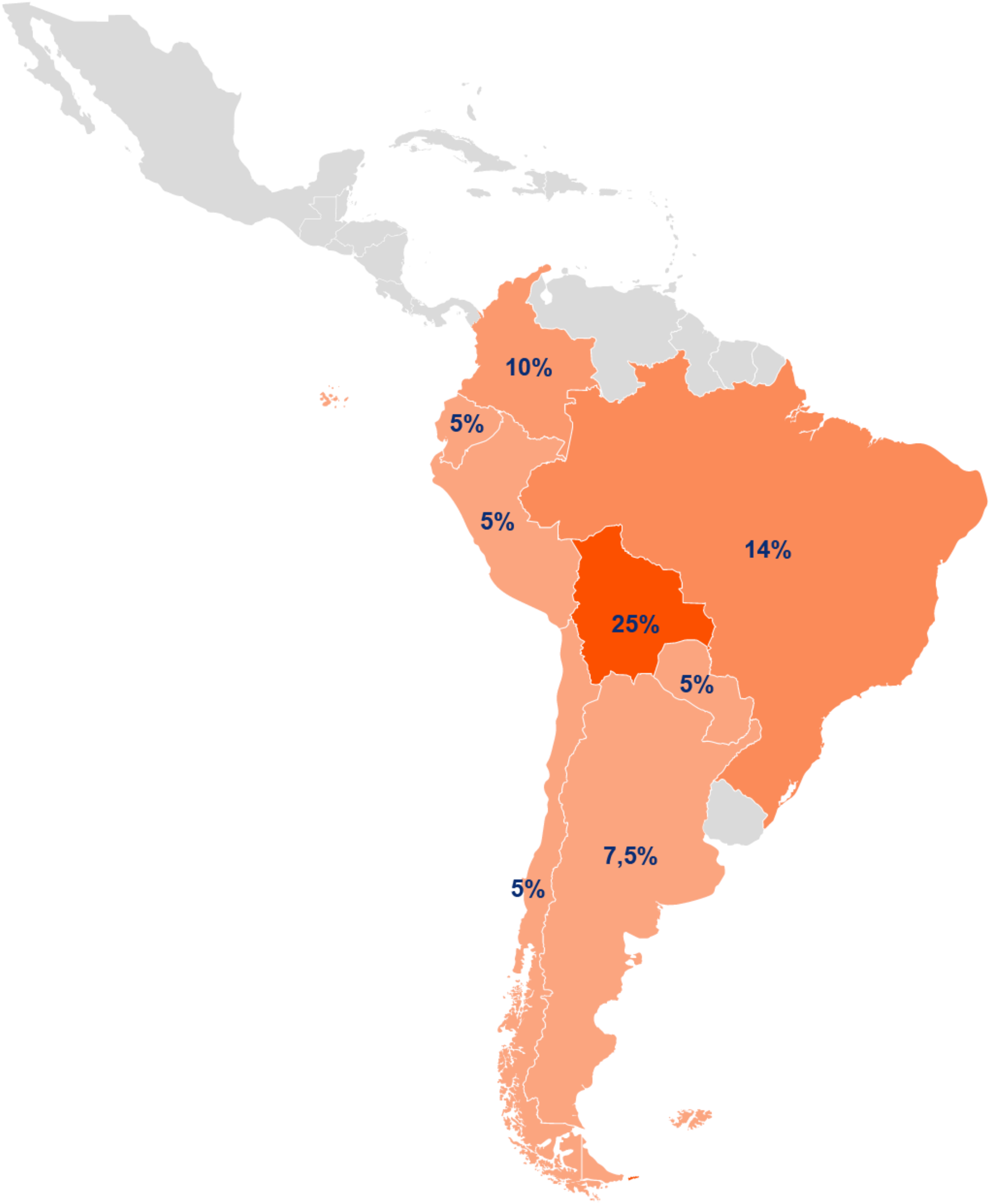
[2] In some states

Figure 9 - Mandates for bioethanol use in LAC



Source: Own elaboration (LAC 2024)

Figura 10 - Mandates for biodiesel use in LAC



Source: Own elaboration (LAC 2024)

4. INNOVATIVE TECHNOLOGICAL SOLUTIONS

There is a growing opportunity in Latin America and the Caribbean to expand biofuel policies beyond land transport —which has traditionally been the main focus due to its high energy consumption— into sectors such as aviation and maritime transport. Although these sectors account a significant share of energy demand and carbon emissions, they have received less attention. Nevertheless, this scenario is evolving, with new regulations beginning to more clearly integrate these sectors, paving the way for their decarbonization. In this context, advanced biofuels —such as Sustainable Aviation Fuel (SAF) for aviation and Hydrotreated Vegetable Oil (HVO) for maritime transport— are gaining relevance as viable solutions to reduce emissions. These fuels also present promising application in heavy industry, where electrification remains particularly challenging.

4.1. Sustainable Aviation Fuels (SAF)

The aviation sector accounts 2.5% of global CO2 emissions, equivalent to around 1 billion tons of CO2 per year (IEA, 2024). in 2021 the industry—represented by the International Air Transport (IATA)—pledged to achieve net-zero carbon emissions by 2050. A similar commitment was adopted by the International Civil Aviation Organization (ICAO) in 2022.

Progress toward these targets is being made through multiple improvements in aircraft design, enhanced engine efficiency, improvements in land transportation, more efficient air traffic control systems and other measures. However, the use of Sustainable Aviation Fuel (SAF) is expected to play the most critical role in enabling the aviation sector to achieve decarbonization goal by 2050 (IATA,2022)

The 4 main strategies[3] to mitigate CO2 emissions and achieve the net-zero scenario in 2050, requires a combination of multiple action, these include:

- ✓ SAF, being responsible for 65%
- ✓ Offsets and carbon capture, with 19%
- ✓ New electric technologies and the incorporation of hydrogen, with 13%
- ✓ Infrastructure and operational efficiency, providing the remaining 3%

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3 https://www.iata.org/en/programs/sustainability/flynetzero/

SAF is a category of advanced biofuels designed to reduce the aviation sector's carbon footprint. SAF is produced from a variety of raw materials and technologies and can partially or fully replace conventional aviation fuel without requiring modifications to engines or supply infrastructure.

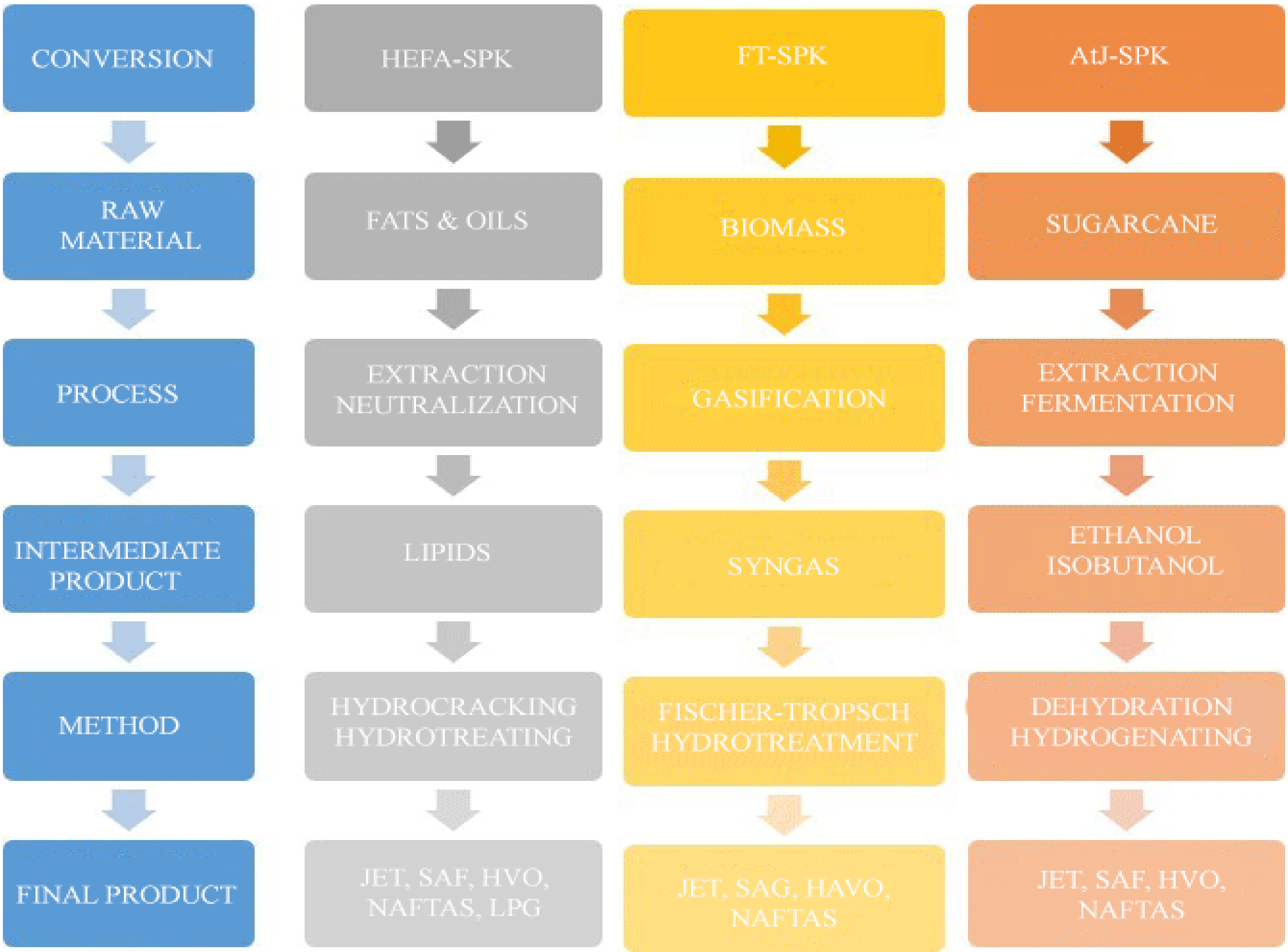
SAF has the potential to decrease GHG emissions by up to 80% compared to fossil fuel. Its use also lowers emissions of atmospheric pollutants—such as particulate matter and sulfur oxides—improving air quality. The extent of these reductions depends on the type of raw material and the conversion process applied.

Currently, there are 11 approved technological conversion pathways[4] and 42 certified raw material sources for the production of SAF (Torroba,2023). These **Technological pathways** refer to the different industrial processes used to convert raw material into a final product with specific characteristics. In the case of SAF, these pathways refer to the approved methods and into developing methods that produce this renewable fuel from diverse sources such as biomass, agricultural residues, vegetable oils, animal fats or even captured CO_2.

Each technological pathway involves different chemical processes, such as **hydrotreating, hydrocracking, gasification, fermentation or catalytic synthesis** that enable the production of a fuel with properties comparable to the fossil kerosene used in aviation. To ensure their safety, compatibility, and performance in aircraft engines, these pathways must comply with international standards—such as **ASTM D7566 OR D1655**—. Not all technological pathways have achieved the same development and processing volume. The following diagram outlines the characteristic of each of the main pathways.

[4] https://www.icao.int/environmental-protection/SAF/Pages/Conversion-processes.aspx

Figure 11 - Three SAF technological relevant pathways



Source: Walter A. et al [5]

HEFA (Hydroprocessed Esters and Fatty Acids) is currently the only technology commercially available at scale for the production of SAF. In 2023, a total production was estimated at 1.29 million metric tons, with approximately 1.21 million produced via HEFA[6], representing about **94% of SAF production**. According to an analysis by the IEA Bioenergy Task, while HEFA has established itself as the predominant technology for SAF, its development has been mainly linked to the production of **renewable diesel**. In recent years, several refineries have begun to

[5] [(PDF) Spatially Explicit Assessment of the Feasibility of Sustainable Aviation Fuels Production in Brazil: Results of Three Case Studies](#)

[6] *https://www.spglobal.com/commodity-insights/en/news-research/latest-news/crude-oil/120623-saf-production-to-triple-to-15-mil-mt-in-2024-but-progress-slow-iata?utm_source=chatgpt.com*

increase the proportion destined to SAF, influenced by regulatory incentives in key markets such as the United States and the European Union. However, economic viability continues to pose a significant challenge, as the production of renewable diesel is often more financially attractive.

Another major challenge for this technology lies in the **availability and sustainability of raw materials**. Although global production of vegetable oils exceeds **220 million metric tons per year**, their exclusive use in SAF would be insufficient to cover projected future demand, which will exceed **400 billion liters by 2050**. Moreover, obtaining low-carbon inputs such as **fats, waste oils and residues (FOGs)** could constrain both SAF and renewable diesel production.

To address these limitations, it is essential to **diversify technological pathways** and promote the development of alternatives such as **FT (Fischer-Tropsch), AtJ (Alcohol-to-Jet) and PtL (Power-to-liquid)**, this approach seeks to ensure a sustainable supply and reduce the current exclusive dependence on HEFA.

SAF can be blended with conventional fuel in proportions ranging from **10% to 50%**, depending on the technology used and aviation safety certifications.

The variety of technological pathways and raw materials suggest a competitive and expanding future market; however, the selection will depend on balancing costs, availability and the actual environmental impact of each alternative.

SAF must meet strict quality and certification standards, such as those set by **ASTM International,** to ensure safety and compatibility with aircraft engines. In addition, initiatives like **CORSIA** (Carbon Offsetting and Reduction Scheme for International Aviation) drive global adoption by requiring verified emission reductions in the aviation sector.

For Latin American countries, the production and supply of SAF represents a strategic opportunity. As CORSIA progresses, the region will need to strength its productive capacity to meet the demands of both intra-regional and international traffic. Nevertheless, in order to comply with international standards, producers must follow certain steps:

- **Sustainability:** Producers must ensure that biofuels comply with environmental criteria, including reductions in GHG emissions and protection of biodiversity. It is crucial to move towards production schemes that promote circularity, through the proper management of waste and the use of by-products.

- **Certification:** Obtain accreditations —such as **RSB (Roundtable on Sustainable Biomaterials)** or **ISCC (International Sustainability and Carbon Certification)** — which guarantee compliance with international standards.
- **Transparency:** Implement traceability systems throughout the supply chain to verify compliance with sustainability standards.

In this sense, it will be essential to develop regulatory and financial mechanisms that foster investment in infrastructure and R&D, ensure the availability of raw materials, and help to cope the high costs associated with production and certification.

There are significant opportunities for the region, both through the valorization of agro-industrial and urban waste, as well as in the development of new crops. The latter will be mainly related to the exploration of agroecological niches, taking advantage of areas and off-season periods that are not currently used for carbon capture through photosynthesis. Nevertheless, considering the gap between the offer of raw material and the growing global demand for SAF, it will be essential to revisit existing regulatory restrictions on the use of commercial oils—such as soybeans and other oilseeds—to ensure their integration under recognized sustainability protocols.

Given the enormous gap between the volume of available raw materials and the increasing demand for SAF, it is desirable that regulatory barriers limiting a major participation of commercial oils —such as soybean and oilseeds— under sustainability protocols be relaxed and lifted.

4.2. Hydrotreated vegetable oil (HVO

Maritime transport accounts for about 3%[7] of global CO2 emissions, according to the International Maritime Organization (IMO). In 2023, during the first scheduled review of its GHG strategy, member states committed to achieve net-zero GHG emissions by 2050, while also establishing more ambitious levels and indicative checkpoints for 2030 and 2040. To achieve these objectives, the maritime sector will need to adopt low-carbon fuels, among which **HVO (Hydrotreated Vegetable Oil)** stands out as a viable alternative

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[7] *https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx*

Hydrotreated vegetable oil, or HVO, is an advanced second-generation biofuel known for its high compatibility with conventional diesel engines and significantly lower environmental impact compared to fossil fuels. Despite its name suggest an exclusivity towards vegetable oils, HVO can also be produced from various raw materials —such as animal fats, Used Cooking Oil (UCO) and tall oil, a by-product of the paper industry.

HVO is obtained through a **hydrotreating** process that use high-purity hydrogen to remove oxygen, sulfur, and other impurities from oils and fats. Under high temperatures and pressure, the fat molecules split and transform into saturated hydrocarbons with properties virtually identical to fossil diesel. This process enhances the fuel's stability and increases its energy density, resulting in a product that surpasses biodiesel in quality and performance —which has certain limitations in terms of stability and compatibility with modern diesel engines.

Over the past decade HVO production increased by approximately 538% to replace diesel. It is estimated that in 2023, production reached 15069000 m^3 accounting for 25% of the total biodiesel output (IICA, 2024)

The global HVO market was valued at $20.82 billion in 2023 and is projected to reach $51.93 billion by 2030 (NMSC, 2024).

HVO represents a renewable and sustainable alternative to conventional diesel, derived from raw materials such as vegetable oils and animal fats. Its production involves a hydrotreating process that removes impurities and reduces oxygen content, resulting in a high-quality and low-emission biofuel, compatible with existing diesel engines

The final product is a fuel **chemically similar to conventional diesel**, enabled to be used in its pure form (**HVO100**) or blended in any proportion. This compatibility eliminates the need for modifications to existing engines or distribution infrastructure

HVO offers multiple **benefits** compared to traditional diesel fuels and other renewable alternatives:

- **Emission reduction:** Its combustion generates **significantly less carbon dioxide (CO_2), particulate matter, and nitrogen oxides (NO_x)** compared to fossil diesel. Depending on the raw material used, greenhouse gas (GHG) emissions **can be reduced by up to 90%** over the fuel's life cycle.

- **High performance in cold climates:** Unlike biodiesel, HVO offers excellent stability at low temperatures, preventing filterability issues and enabling its use in extreme weather without the need of additional additives.
- **Full compatibility:** HVO can be used without restrictions in existing diesel engines and fuel distribution infrastructure, facilitating its adoption at no additional cost in new technologies.

These qualities position HVO as a key solution for hard-to-decarbonize sectors such as **heavy transport, maritime and industry**, where electrification remains limited.

Despite its advantages, HVO development still faces significant **challenges**:

- **High production costs:** Hydrotreatment process requires high-purity hydrogen and additional refining steps, making HVO more expensive to produce than biodiesel —estimated values between **$1.5 and $2.5 per liter**—. Nevertheless, these costs can be partially offset by their higher efficiency and lower environmental impact
- **Sustainable hydrogen availability** HVO production relies on a supply of high-purity hydrogen, the environmental impact of which varies depending on its source. To maximize the climate benefits of HVO, it is key to develop **green hydrogen** (produced from electrolysis with renewable energies) instead of fossil-based hydrogen.
- **Sustainable raw material access:** Rising global demand for biofuels is increasing pressure on vegetable oils and organic waste availability. To avoid negative impacts on food security and land use, it is essential to diversify raw material sources and optimize traceability under rigorous sustainability standards.

5. SUCCESS STORY AND LESSONS LEARNED

5.1. Brazil: A model of biofuels success

Brazil is the world's second-largest producer of ethanol —after the United States— and has developed one of the most advanced and sustainable biofuel industries globally. This achievement is the result of a combination of public policies, technological innovation and effective integration between the agricultural and energy sectors. Since the 1970s, with the implementation of the National Alcohol Program (Proálcool), Brazil has actively promoted sugarcane ethanol as an alternative to fossil fuels. Today, the country boasts a robust distribution infrastructure capable of supplying one of the world's largest fuel vehicle fleets.

Proálcool program emerged as a response to the oil crisis and played a pivotal role in the creation of a market for ethanol through tax incentives, financing for production and infrastructure for its distribution. A major turning point came in 2003 with the adoption of flex-fuels vehicle. Currently, more than 80% of light cars in Brazil are capable of running on gasoline, ethanol or a mixture of both, which ensure a stable market for biofuel. This flexibility, coupled with a blending mandate ranging from a minimum of 18% to a baseline that currently stands at 27% anhydrous ethanol in gasoline, solidifies ethanol's presence in the domestic market.

The success of the Brazilian model also lies in its integration with the agro-industrial sector. Favorable climatic conditions make Brazil particularly well-suited for sugarcane cultivation, enabling high efficiency and low production costs. In addition, sugar and ethanol industries have developed a synergistic relationship where ethanol serves as a financial stability mechanism against fluctuation in sugar prices. A key element that reinforces the sustainability of the model is the use of sugarcane bagasse for cogeneration of electricity, which allows many facilities to be energy self-sufficient and contribute to the national electricity system.

In 2017, Brazil implemented RenovaBio program, a regulatory framework designed to reduce emissions in the biofuel sector. Under this scheme, decarbonization goals were set for fuel distributors, and Decarbonization Credits (CBIOs) were introduced. These approaches incentivize the production of biofuels with a lower carbon footprint.

The RenovaBio program employs a measurement approach based on the generation and commercialization of CBIOs. To determine the emissions associated with each biofuel and determine the amount of CBIOs that can be emitted, the program uses diverse factors and methodologies, such as Carbon Emission Factor, which quantifies greenhouse gas emissions across the entire biofuel's life cycle, and Biofuel Certification, which requires producers to demonstrate the reduction of GHG emissions in their production chain.

The process is governed by the RenovaBio Registry (ANP Resolution No. 758/2018), which establishes the parameters and methodologies for energy efficiency certification and emission reduction. The certification is conducted by entities accredited by the National Agency of Petroleum, Natural Gas and Biofuels (ANP), including independent auditors and specialized consultancies, ensuring the integrity and accuracy of emissions calculation. Based on these certifications, CBIOs are allocated to each biofuel producer and can be traded on the carbon market as an instrument to meet the emission reduction targets set by the RenovaBio program.

The National Bank for Economic and Social Development (NBDES) has played a crucial role in the consolidation of the sector by providing financing for the biofuel industry expansion, plant modernization and the development of new technologies. Through its NBDES RenovaBio program, launched in 2021, the bank has financed initiative to enhance the energy and environmental efficiency of biofuel plants. To date, the program has approved 12 operations totaling nearly USD195 million in financing, benefiting companies such as FS Bioenergía and Alcoeste, which have optimized their production processes and obtained sustainability certifications In addition, NBDES has supported the production of second-generation (2G) ethanol through a recent financing of R$1 billion for Raízen company, which is expected to boost national capacity by 440 million liters of biofuel.

In October 2024, Brazil enacted the Future Fuel Law, aimed to enhancing the competitiveness of ethanol and other biofuels within the energy transition. The legislation stablishes national programs to promote sustainable fuels and reduce emissions in the transport sector. Among its key initiatives are the National Sustainable Aviation Fuel Program (ProBioQAV), which mandates a gradual reduction of emissions from domestic flights through the adoption of sustainable biofuels —starting with 1% in 2027 and increasing to 10% by 2037. Likewise, the

National Green Diesel Program (PNDV) establishes minimum annual quotas for blending green diesel with fossil diesel, regulated by the National Council for Energy Policy.

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Another pillar of the law is the National Program for the Decarbonization of Natural Gas Producers and Importers and Biomethane Incentives, aimed to promote the research, production and use of biomethane and biogas into the Brazilian energy matrix, with emission reduction targets starting at 1% in 2026 to 10% in the long term. Additionally, the law raises the mandatory ethanol blend in gasoline from 22% to 27%, with the possibility to increase it to 35% in the future. In parallel, it establishes a gradual rise in the biodiesel blend in diesel, increasing by one percentage point annually from 2025 until reaching 20% in 2030.

Brazil experience shows that the development of biofuels requires a comprehensive strategy integrating regulation, technology and a well-structured industry. Long-term policies have provided sectoral stability, while the availability of flex-fuel vehicles has played a crucial role in the adoption of ethanol in the domestic market. Sustainability has also been a key pillar, with a production based on renewable sources and processes that significantly reduce carbon emissions. Given the extensive experience, successful implementation and tangible results, this framework should be considered at a regional level to foster the development of low-emission biofuels across Latin America and the Caribbean.

5.2 Lessons learned

Brazil's experience offers valuable lessons for Latin America and the Caribbean on how the development of biofuels can be effectively driven by long-term public policies, technological advances, and integration between the agricultural and energy sectors. Nevertheless, the Brazilian experience also underscores important challenges. The expansion of agribusiness for crops such as sugarcane and soybean—partly destined for the production of biofuels—, has been linked as a factor to deforestation, biodiversity loss, and land-use conflicts in environmental sensitive areas such as the Amazon and the Cerrado. These socio-environmental impacts have drawn international criticism, emphasizing the need to prevent indirect land-use changes (ILUC) and ensure that production follows standards that safeguard both ecosystems and the rights of local communities.

Therefore, one of the key lessons is that the growth of the sector must be accompanied by strong sustainability frameworks, environmental and social monitoring mechanisms, and active involvement from rural communities. Ensuring that biofuels expansion simultaneously contributes to emission reductions, environmental conservation and local development will be crucial for stablishing a sustainable and competitive regional model.

6. CONCLUSIONS

6.1. Synthesis of opportunities and challenges

In the regional context, low-carbon biofuels emerge as a vital solution for decarbonizing critical sectors —such as land, air and maritime transport—where reliance on fossil fuels remains significant.

In 2023, global liquid fuel production reached 180,544 thousand m^3 (IICA, 2024), with LAC contributing 27%, equivalent to 47,827 thousand m^3. Brazil led regional production by far, accounting for nearly 25% of global production and 93% of total LAC production (SieLAC, 2024). In the region, bioethanol and biodiesel accounted for 81% and 19% of liquid biofuel production, respectively, in 2023. That year, domestic consumption across the region averaged approximately 69 liters per capita.

LAC holds competitive advantages to consolidate its leadership in this sector. The region benefits from optimal agro-ecosystems —including adequate temperature, water and soils— complemented by efficient and technologically advanced production chains. The competitiveness of crops such as sugarcane, soybeans and palm oil has enabled it to stablish a strong presence in international markets. Moreover, the implementation of regulatory frameworks with blending mandates in several countries contributes to a stable demand, reinforced by industry associations that have promoted standards and certifications. In addition to these strengths, there is a growing potential to generate employment in rural communities to boost both economic and social development.

Growth prospects are driven by rising demand for biofuels in hard-to-electrify sectors —such as aviation and maritime transport. The integration of advanced biofuels with green hydrogen and carbon capture will offer new possibilities to further reduce emissions from the transport sector. In addition, advances in biotechnology and the optimization of biorefineries can enhance production efficiency and create synergies with other renewable technologies, such as biogas. Brazil's experience with incentive and certification systems, provides a model that can be replicated by other countries in the region to promote emission reductions and foster integration with the hydrocarbon industry.

Nevertheless, the sector's expansion will depend on meeting increasingly demanding sustainability requirements in international markets. Issues such as indirect land-use change, biodiversity loss, by-product management, and potential competition with food crops, pose challenges that need to be addressed. Additionally, the rise of disruptive technologies in other renewable energy sources could shift the current market balance.

In this scenario, policies that ensure stability and predictability will play a crucial role, with incentives aligned with the socio-environmental benefits of biofuels. It is also key to strengthen logistics and storage infrastructure to reduce costs and optimize marketing. Additionally, the implementation of traceability and monitoring systems powered with advanced technologies will guarantee that regional production adhered to the environmental and social standards governing the international trade in sustainable fuels

In order to consolidate its position in global markets, LAC must need to strengthen financing mechanisms throughout the entire production chain and foster regional cooperation in research, innovation, and certification. These efforts will make it possible to fully harness the potential of low-carbon biofuels as a key instrument for advancing the region’s energy transition and sustainable development.

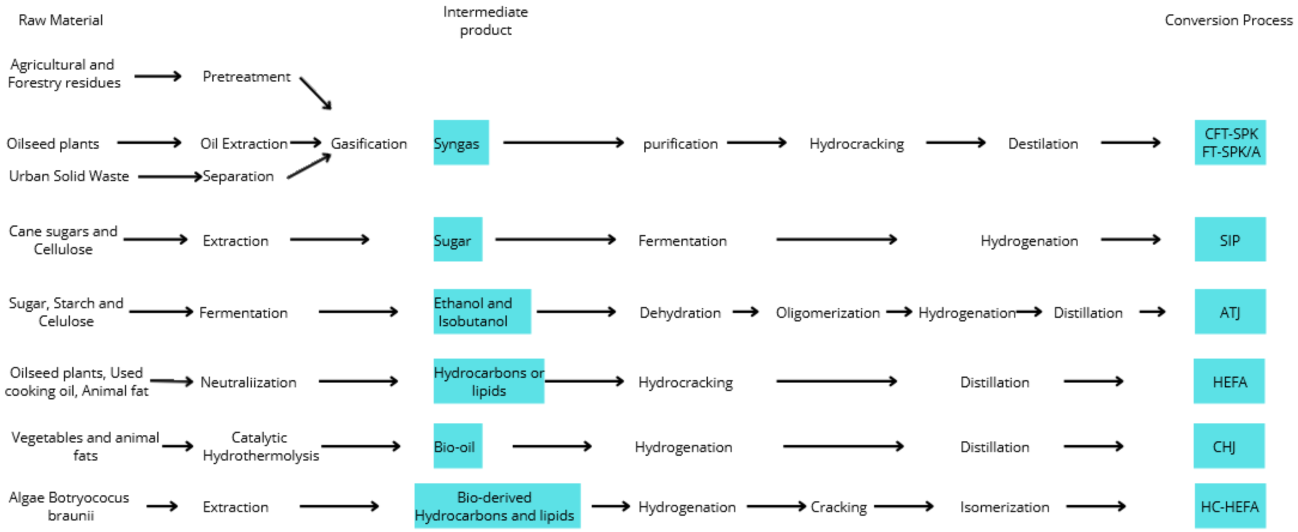
ANEXOS

A. ASTM Approved Pathways for SAF Production

PATHWAY	ASTM	NAME	YEAR	RAW MATERIAL	BLEND
1	D7566 Annex 1	**FT-SPK** *Fischer-Tropsch -* *Synthetic Paraffinic Kerosene*	2009	**Lignocellulosic biomass:** Agricultural and forestry residues (sugarcane bagasse and stubble, and municipal wastes)	Up to 50%
2	D7566 Annex 2	**HEFA-SPK** *Hydroprocessed Esters and Fatty Acids -* *Synthetic Paraffinic Kerosene*	2011	**Oils and fats:** Camelina, Jatropha, castor oil, palm oil, used cooking oils and animal fat	Up to 50%
3	D7566 Annex 3	**HFS-SIP** *Hydroprocessed Fermented Sugars - Synthetic Iso-Paraffins*	2014	**Microbial conversion of sugars to hydrocarbons:** sugar cane, cassava, sorghum and maize	Up to 10%
4	D7566 Annex 4	**FT-SPK/A** *Fischer-Tropsch -* *Synthetic Paraffinic Kerosene with Aromatics*	2015	**Lignocellulosic biomass:** Agricultural and forestry residues (sugarcane bagasse and stubble, and municipal wastes)	Up to 50%
5	D7566 Annex 5	**ATJ-SPK** *Alcohol to jet - Synthetic Paraffinic Kerosene* Isobutanol / Etanol	2016 2018	**Biomass used for sugar production and lignocellulosic biomass:** Sugarcane, cassava, bream, maize, ethanol	Up to 50%
6	D7566 Annex 6	**CHJ** *Catalytic hydrothermolysis jet fuel*	2020	**Triglyceride-based raw material:** waste, algae, soy, Jatropha, camelina and carinata	Up to 50%
7	D7566 Annex 7	**HC-HEFA-SPK** *Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene*	2020	Biologically derived hydrocarbons, fatty acid esters, triterpenes produced by the algae species Botryococcus braunii.	Up to 10%
8	D7566 Annex 8	**ATJ-SPK/A** *Alcohol to jet - Synthetic Paraffinic Kerosene with Aromatics*	2020	C2-C5 alcohols from biomass	Up to 50%
9	D1655 Annex 1	**Co-HEFA in conventional oil refining** *Hydroprocessed Esters and Fatty Acids -* *Synthetic Paraffinic Kerosene*	2021	**Oils and Fats:** Vegetable oils, animal fats, and used cooking oils processed together with petroleum	Up to 5%
10	D1655 Annex 1	**FT Co-processed in conventional oil refinery** *Fischer-Tropsch*	2021	**Lignocellulosic biomass:** Agricultural and forestry residues (sugarcane bagasse and stubble, and municipal wastes)	Up to 5%
11	D1655 Annex 1	**HEFA Co-processed** *Hydroprocessed Esters and Fatty Acids -*	2021	**Oils and fats:** Camelina, Jatropha, castor oil, palm oil, used cooking oils and animal fat	Up to 10%

Source: Own elaboration based on ICAO

A. Process Synthesis



Source: (Cabrera & Melo de Sousa, 2022)

B. Macos Normativos en ALC

Country	Ethanol (Mix)	Biodiesel (Mix)	Regulatory Framework
Argentina	E12 (12%)	B5 (5%)	Law No. 27.640/2021 establishes the biofuel promotion regime by setting a mandatory cut of 5% for biodiesel and 12% for bioethanol. Nevertheless, the blending percentages have varied over time since the values can be modified by the Executive Branch according to market conditions.
Bolivia	E25 (25%)	B25 (25%)	Supreme Decree N. 5135 (March 2024) increased the blending mandate bioethanol and biodiesel to 25%.
Brazil	E27 (27%)	~B13 (about 12%)	Brazil has one of the most advanced biofuels programs in the world. The mandate for ethanol was established by Law No. 8.723/1993, and for biodiesel by Law No. 11.097/2005. The blending percentages are adjusted periodically by the National Energy Policy Council (CNPE).
Chile	No especificado (uso promovido, sin mandato)	B5 (5%)	Law No. 20.257/2008 establishes the basis for the promotion of non-conventional renewable energies, including biofuels, without a specific mandate for ethanol. Biodiesel is promoted through a blending requirement of 5%.
Colombia	E10 (10%)	B10 (10%)	The regulatory frameworks of the Ministry of Mines and Energy have promoted the production of biofuels, with percentages established by resolutions that have varied according to market conditions and availability of raw materials..
Costa Rica	E7 (7%)	Non-specific	Executive Decree No. 36.447-MINAE, which outlines the National Biofuels Policy, promotes the use of biodiesel; nevertheless, it does not impose a specific blending mandate.
Ecuador	E5 (5%)	B5 (5%)	The Law on the Promotion and Development of the Production of Biofuels lays the foundations for the promotion of these fuels. For ethanol there is no mandatory mandate, but the gasoline marketed (ECOPAÍS E) includes a blend; for biodiesel a 5% blending mandate exists (still pending operationalization).
El Salvador	E10 (10%)	Non-specific	The 2011 Law for the Promotion and Promotion of Biofuels establishes the mandatory use of ethanol in gasoline.
Guatemala	E5 (5%)	Non-specific	The Biofuels Promotion Act of 2008, along with the General Regulations of the Fuel Alcohol Act AG-159-2023, establishes an obligation for the minimum use of ethanol of 5% in gasoline from 1 January 2025.
Jamaica	E10 (10%)	Non-specific	The National Ethanol Program, implemented in 2008, establishes the mandatory use of E10 in the country.
Mexico	E10 (in some states)	Non-specific	The 2008 Law on the Promotion and Development of Biofuels establishes the basis for the use of biofuels; while there is no federal mandate, some states have adopted E10.

Panamá	E5 (5%)	Non-specific	Law No. 42/2011 establishes the mandatory use of ethanol in gasoline. The use of biodiesel is promoted, without a specific mandate.
Paraguay	E30 (30%)	B5 (5%)	Law No. 2748/2005 establishes the mandatory use of biofuels, and the blending percentages are defined by the Executive.
Perú	E7.8 (7.8%)	B5 (5%)	Law No. 28054/2003 promotes the biofuels market and establishes the percentages of mandatory blending.
República Dominicana	E15 (15%)	Non-specific	Law No. 57-07 on Incentives for the Development of Renewable Energy Sources and its Special Regimes establishes the mandatory use of ethanol in gasoline.
Uruguay	E8,5 (8,5%)	0%	Law No. 18.195/2007 established the framework promoting agrofuels; nevertheless the biodiesel mandate was repealed in 2022, leaving only an ethanol blending requirement in place.

Source: Own elaboration

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