

The global outlook of biofuels: comparative case studies of Brazil, the United States, and the European Union

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ABSTRACT

This study reviews the future of internal combustion cars and their sustainability challenges, with a particular focus on the role of biofuels in the decarbonization of transport. It presents the technological, economic, and environmental aspects of conventional and alternative energy resources, especially the generational development

Abbreviations: ANFAVEA, Associação Nacional dos Fabricantes de Veículos Automotores (Brazilian Association of Automotive Vehicle Manufacturers): It is the entity that bring together automobile, light commercial, truck, bus, agricultural and construction machinery manufacturers; BEV, Battery Electric Vehicle: It is a type of electric vehicle that runs entirely on electricity stored in high-capacity rechargeable battery packs; CORSIA, Carbon Offsetting and Reduction Scheme for International Aviation: The first global market-based scheme that applies to a sector. It complements other aviation in-sector emissions reductions efforts such as technological innovations, operational improvements and sustainable aviation fuels to meet the ICAO aspirational goal of carbon neutral growth; EEA, European Environment Agency: It is an agency of the EU that serves as the central hub for providing data, independent information, and expert advice on the state of the environment, climate change, and sustainability to support EU policy goals; Eurostat, Statistical Office of the European Union: It publishes official, harmonised statistics on the European Union and the euro area, offering a comparable, reliable and objective portrayal of Europe's society and economy; EV, Electric Vehicle: It refers to any vehicle powered wholly or partly by an electric motor and battery rather than an internal combustion engine; FLEX, Flex-fuel, FFV, Flexible Fuel Vehicle: These are automobiles designed to run on gasoline or a blend of gasoline and ethanol using the same engine and fuel tank; GHG, Greenhouse Gas: These are gases in the Earth's atmosphere that trap heat, causing the greenhouse effect; GMO, Genetically Modified Organism: Refers to any plant, animal, or microorganism, whose genetic material (DNA) has been altered using genetic engineering techniques to introduce, remove, or enhance specific traits; HVO, Hydrotreated Vegetable Oil: It is a type of renewable, paraffinic diesel fuel produced from raw materials such as waste vegetable oils, animal fats, and other residues, rather than crude oil; IEA, International Energy Agency: It is an autonomous intergovernmental organization that provides data, analysis, and policy recommendations to ensure secure, sustainable, and clean energy; ILUC, Indirect Land Use Change: It can occur when land previously devoted to food or feed production is converted to produce biofuels, bioliquids and biomass fuels. In that case, food and feed demand still needs to be satisfied, which may lead to the extension of agricultural land into areas with high carbon stock such as forests, wetlands and peat land, causing additional greenhouse gas emissions; LCA, Life Cycle Assessment: It is a systematic, ISO-standardized method used to evaluate the environmental impacts of a product, process, or service throughout its entire existence, „from cradle to grave”; OECD-FAO, Organisation for Economic Cooperation and Development (OECD) and Food and Agriculture Organization (FAO): Together, they produce the annual OECD-FAO Agricultural Outlook, a report analyzing 10-year trends in global agricultural markets; RED, Renewable Energy Directive (2009/28/EC): The Renewable Energy Directive sets targets to increase the EU's renewable energy use. It supports cooperation between EU countries towards this goal; RED II, Renewable Energy Directive II (2018/2001/EU): The revision of RED – Recast to 2030; RED III, Renewable Energy Directive III (2023/2413/EU): The revision of RED II; RFS, Renewable Fuel Standard: It is a federal program that mandates the incorporation of renewable fuels into the nation's transportation fuel supply; SAF, Sustainable Aviation Fuel: Non-petroleum-based alternative to conventional jet fuel, often made from waste oils, agricultural residues, or synthetic sources. Lifecycle CO₂ emissions can be reduced by up to 80% using SAF; SDGs, Sustainable Development Goals: SDGs were adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity; Statista, It is a leading German online platform and business intelligence company that provides aggregated data, market research, and insights from over 22,500 sources covering 170 industries; UCO, Used Cooking Oil: It refers to any vegetable oil or animal fat that has been used for cooking or frying food in the food processing industry, restaurants, and households; UN-FAO, Food and Agriculture Organization of the United Nations: A specialized agency of the United Nations that leads international efforts to defeat hunger.

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ILUC
HVO
Waste-to-fuel
Decarbonization

of biofuels, sustainability issues, and global market trends. It highlights ILUC risks, changes in regulatory frameworks, and strategies of different countries, particularly through examples from Brazil, the United States, and the EU. Comparing the EU, Brazil, and the USA is essential, as the three largest biofuel producers operate under different conditions, leading to distinct policy approaches to developing and decarbonizing both biofuels and, more broadly, the transport sector. For instance, Brazil continues to prioritize sugarcane-based bioethanol, while the EU increasingly focuses on the expansion of electric vehicles – partly due to less favorable agricultural conditions, which limit its biofuel production potential. The study concludes that the long-term role of internal combustion engines is gradually decreasing, while renewable energy sources and advanced biofuels play a significant role during the transition period in achieving climate protection objectives. This conclusion is strongly supported by the current regulatory environment, which points in this direction across the largest biofuel-producing regions (with the exception of Brazil), reflecting policy decisions and directives that increasingly favor the transition away from conventional engine technologies. Finally, it proposes future research directions, particularly in sustainability, technological developments, and regulatory instruments.

1 Introduction – The problems of internal combustion vehicles

Internal combustion engines have been improved over many decades and are now a mature, reliable technology based on extensive automotive supplier networks. Another key factor behind their long-standing dominance is the relatively low cost and high energy density of liquid fuels, as well as the well-established infrastructure for their transport and storage. Unlike alternative propulsion systems, liquid fuels can be distributed without the need for extensive new linear infrastructure, relying instead on existing refueling networks. Moreover, fuels can be stored for extended periods without significant degradation under appropriate conditions [1], and refueling is rapid, ensuring high vehicle availability. The power output of modern combustion engines is sufficient for the efficient transport of goods and, in the case of passenger cars, for dynamic driving. As a result, internal combustion vehicles continue to effectively meet the current needs of economic actors and society; no wonder that they have become the most important means of meeting mobility needs.

1. Despite these advantages, two fundamental challenges question the long-term viability of ICE-based transport systems. Emissions associated with fuel combustion – including greenhouse gases, aerosols, and solid particles – pose significant environmental and health risks, as it has now been demonstrated that greenhouse gas emissions from internal combustion vehicles contribute to global climate change [2–6]. According to IEA data, private cars and vans accounted for more than 25% of global oil consumption and about 10% of global energy-related CO₂ emissions in 2023 [7]. Especially in metropolitan environments, the combustion products of internal combustion engines [8,9], along with additional emissions associated with car traffic (brakes, tire wear, dust sprays), significantly contribute to poor air quality and thus threaten human health [10–12]. A study from 2023 revealed that premature death rates in Chinese cities increased by 17.5% due to road congestion and high levels of air pollution (Pm 2.5, ozone) [13]. The ban on leaded gasoline in the U. S. in 1996, the advent of cleaner new vehicles resulting from strict emission standards, and the spread of electric and hybrid vehicles have led to significant improvements in air quality in major cities such as Los Angeles and Chicago [14].
2. The Earth, as a celestial body, is finite, and therefore the amount of crude oil that can be extracted from organic matter deposited over geological time is also limited in the long term [15,16]. However, in the short to medium term, needs are generally met [17,18]. Globally, oil consumption increased by 1% and production by 0.9% annually between 2014 and 2024. Yet, in 2024, oil held the largest share in the energy mix (33.5%), though this share is slightly decreasing due to the rise of renewables (5.6%) [19]. Advances in hydrocarbon extraction technology have made extraction more efficient, allowing the use of sites and petroleum carriers previously deemed economically or technically unrecoverable [20,21]. However, this does not

resolve the core issue; it merely extends the timeline for the availability of petroleum-based fuels.

In response to these challenges, numerous technological improvements—such as engine downsizing, after-treatment systems, and aerodynamic optimization—have been introduced to reduce emissions and improve efficiency [22–24]. However, these incremental developments face diminishing returns, and further substantial reductions in emissions from ICE technology alone appear increasingly limited [24,25].

In the long term, the outlook for fuel production and supply security remains bleak [26,27]. The production of biofuels and alternative synthetic fuels could serve as a potential solution, theoretically replacing traditional fuels derived from crude oil [9,26,28–30]. Under certain conditions, these fuels can achieve significantly lower life-cycle greenhouse gas emissions compared to conventional fossil fuels [31]. If sustainable production of biofuels and synthetic fuels becomes feasible, they could be considered limitless and environmentally friendly energy resources [32–34]. However, their large-scale deployment is constrained by economic, technological, and sustainability challenges, including land-use impacts and feedstock availability.

Overall, the political, scientific, and technical effort to revolutionize road transport is well-supported. The goal is clear: to create a sustainable transportation system and, for this purpose, to promote electric and “fuel cell” (mainly hydrogen) technologies in road transport, which are less harmful to the environment, replacing internal combustion engines. However, for electric and/or hydrogen-powered vehicles to become common and eventually entirely replace internal combustion vehicles, it is essential that newer technologies are affordable and capable of meeting users' needs in real-world conditions and practical use. Biofuels will play an important role during the transition period, helping to partially lower the transport sector's carbon footprint until this shift occurs.

Despite the well-documented environmental and resource-related limitations of internal combustion engine-based transport systems, the transition towards low-carbon mobility remains uneven and regionally differentiated. In this context, biofuels are often positioned as a transitional solution, yet their sustainability outcomes are highly dependent on regulatory design, implementation, and regional economic structures. While a substantial body of literature addresses the technical and environmental aspects of biofuels, comparative analyses of how different policy frameworks shape sustainability outcomes remain limited.

To address this gap, this study adopts a comparative policy perspective and focuses on major biofuel-producing regions, including the United States, Brazil, and the European Union. The analysis is guided by the following research questions:

1. How do regulatory frameworks influence the sustainability performance of biofuels in different regions (e.g., the United States, Brazil, and the European Union)?

2. To what extent do policy instruments account for indirect land-use change (ILUC) and broader environmental externalities?
3. What are the key trade-offs between economic viability, environmental sustainability, and energy security in current biofuel policy regimes?

This study is grounded in the literature on sustainability transitions and policy mix theory, which emphasize the role of coordinated policy instruments in shaping technological pathways and environmental outcomes. From this perspective, biofuels are not evaluated solely as technological solutions but as outcomes of interacting regulatory, economic, and institutional frameworks. The analysis therefore considers how different policy mixes—such as blending mandates, subsidies, and sustainability certification schemes—affect both market development and environmental performance. This approach allows for a more nuanced assessment beyond purely techno-economic or life-cycle-based evaluations.

2. Methodology

This study represents a comprehensive literature review aimed at analyzing the short- and mid-term prospects of biofuels. Its primary objective was to synthesise a wide range of scientific and practitioner-oriented sources to map the current state of the biofuels sector, its development trajectories, challenges, and future outlook. Because studying the role of biofuels is inherently complex—spanning technological, social, economic, and political dimensions—and because we also sought to analyze the spatial dimension of real-world deployment, we adopted a research-question-driven, problem-oriented **Targeted Literature Review (TLR)** with a **comparative framework synthesis**. The approach was chosen to address predefined, policy-relevant research questions on biofuel governance, feedstock lifecycle performance, and market dynamics across Brazil, the United States, and the European Union.

Search strategy. We searched **Scopus** and **Web of Science** (2008–2025), complemented by **institutional grey literature** (e.g., IEA, European Commission, EEA, EPA, ANP-Brazil, Eurostat), and snowballing from key reviews and policy documents.

Search term families combined concepts for *biofuel**, *policy/mandate/standard*, *LCA/CI/ILUC*, *EV/transport decarbonization/SAF*, and region tags (*Brazil, United States/US, European Union/EU*).

Eligibility criteria. Inclusion: peer-reviewed articles or reputable institutional reports; transport focus; quantitative indicators or explicit policy content; relevance to at least one of the comparative domains (policy instruments, feedstock/LCA, market dynamics, sustainability safeguards). Exclusion: non-transport sectors; non-traceable data; non-comparative commentary without empirical basis.

Source quality and grey literature. Peer-reviewed sources were prioritized (IEA, OECD-FAO, EEA, Eurostat reports and data). Grey literature was included when methods and data provenance were transparent, the publisher was authoritative,

Limitations. As a targeted, problem-oriented review, this study is **not exhaustive**. We mitigate selection bias through transparent reporting of sources, search strings, and eligibility criteria, and by triangulating peer-reviewed evidence with institutional datasets.

The research draws upon several categories of sources:

1. Scholarly Literature (196 sources): Peer-reviewed journal articles, conference proceedings, and book chapters formed the core of the analysis. Preference was given to the most recent and relevant publications (primarily those published within the last 5–7 years), while also incorporating seminal, widely cited works that provide enduring theoretical or conceptual frameworks still pertinent in contemporary discourse.
2. Analyses, Reports, and Statistical Databases (28 sources): Reports and datasets published by international and national organisations

(e.g., IEA, EEA, Statista, Eurostat, ANFAVEA, national energy and climate assessments) were included to enable an empirical basis for the study. These sources provided quantitative data and trend information critical for objectively assessing industry performance, technological development, and market dynamics.

3. National and EU-Level Directives, Regulations, and Policy Documents (7 sources): To understand the regulatory and policy context shaping the biofuels landscape, relevant national and European Union directives, regulations, and policy documents were reviewed. These sources offered insights into the legal frameworks, strategic objectives, and sustainability criteria affecting biofuel deployment and integration.

The selection of sources was based on a systematic search strategy, employing multiple keyword combinations (e.g., biofuels future, bio-energy policy, renewable energy statistics, sustainability of biofuels, EU renewable directives) across several academic databases (including Scopus, Web of Science, and Google Scholar). While English-language publications constituted the majority of the material reviewed, significant contributions in Hungarian and other European languages were also incorporated where relevant. In the course of the literature review, preference was given to peer-reviewed sources, complemented by the targeted use of reports and data from established professional organizations.

Content analysis of the collected material was conducted using qualitative synthesis techniques. Key themes, trends, and discrepancies across sources were identified and compared, with particular attention paid to technological innovations, policy frameworks, economic impacts, and sustainability issues. Where feasible, quantitative trend analysis was performed to examine biofuel production, consumption, and market share developments within the EU and selected key countries. Within [Section 3.1](#), [Section 4.1](#), [Section 4.2](#) and [Section 4.3](#), quantitative trend analysis was employed to monitor the evolution of biofuel production. It should be noted that the data were not subject to normalization or adjustment, but were assessed as originally reported.

The methodology was designed to provide a robust, comprehensive, and multi-dimensional understanding of the short- and mid-term future of biofuels, integrating scientific evidence, regulatory context, and empirical data.

3. Biofuels

Biofuels are liquid or gaseous fuels used in transportation produced from biomass, such as biodegradable agricultural, forestry, or fishery products, waste, residues, or biodegradable industrial and household waste [35]. The most common forms are alcohol-based bioethanol, used as a petrol additive, and oil-based biodiesel, used as a diesel additive. The former is mainly produced from starch- and sugar-containing crops (e.g., wheat, maize, barley, sugar beet, and sugarcane), while the latter comes from vegetable fats (such as rapeseed, sunflower seed, soybean, and palm seed) [36–40]. According to the raw materials used for production and the technology level, biofuels are categorized into first-, second-, and third-generation biofuels [41–44]. The conventional generational classification of biofuels is increasingly questioned, as it fails to capture the technological and feedstock overlaps that characterize modern production pathways. Hydrotreated Vegetable Oil (HVO) illustrates this overlap: although its hydroprocessing technology corresponds to second-generation standards, it can be produced from both food-grade oils and waste-derived feedstocks. As a result, contemporary sustainability assessments are shifting away from rigid generational taxonomies toward pathway-specific evaluations that account for carbon intensity and Indirect Land-Use Change (ILUC) risks.

The main advantage of biofuels is that they originate from renewable resources [45–49]. Some biofuels significantly reduce greenhouse gas emissions [50–53]. While advanced biofuels theoretically offer lower life-cycle emissions, this outcome is not guaranteed ([Table 1](#)). The actual

Table 1

Comparison of Biofuel Pathways. Own editing. Source: [60–62].

Category	Representative Feedstocks	CO ₂ Reduction Potential*	Key Technical & Policy Challenges
1st Gen (Food-based)	Corn, Sugarcane, Rapeseed, Palm oil	40%–70%	Food vs. Fuel debate; high ILUC risk; land-use constraints.
2nd Gen (Advanced / Waste-based)	Straw, Wood residues, Used Cooking Oil (UCO), Animal fats	80%–95%	Complex biochemical/thermochemical conversion; logistics of biomass collection.
3rd Gen (Algae-based)	Microalgae, Seaweed	Variable (up to >100%)	High energy intensity in cultivation and harvesting; currently high CAPEX.
Technological Overlap (e.g., HVO/HEFA)	It can be produced from both first- and second-generation oils alike	50%–90%	Feedstock traceability; competition for limited waste-oil supplies.

*Life-cycle GHG savings compared to fossil fuel baselines. The values vary depending on the feedstock used (e.g., sugarcane, corn).

environmental footprint depends on feedstock sourcing (ILUC risk), process yields, and energy intensity; unfavorable local energy inputs can negate these benefits or significantly drive up costs, even for third-generation pathways [54–59].

The production of first-generation biofuels mainly comes from food crops. The disadvantages and ethical issues of first-generation biofuels are discussed in various literature sources [41,63–66]. Most researchers agree that first-generation biofuels negatively affect food production [55,67–69]. This is due to two reasons: the raw materials could also be used for food production, and the land for biofuel production could instead be used for food production. Therefore, the share of first-generation biofuels in the EU's 2030 targets is limited to a maximum of 7%, as specified by the RED III Directive [70,71].

The rapid adoption of first-generation biofuels was facilitated by existing infrastructure, as these technologies relied on current agricultural and processing capacities, enabling development to begin quickly [72]. Furthermore, by-products from production, such as high-protein residues, have significant economic value because they can be used as feed, thereby supporting the agricultural sector, stimulating economic growth, and reducing costs when used within the supply chain [73–75]. These factors have played a crucial role recently, but environmental, food safety, climate, and sustainability concerns have also prompted decision-makers to reconsider strategies to make the transport sector greener. Consequently, first-generation biofuels are gradually being phased out in most countries as sustainability challenges and ILUC effects exert increasing pressure to prioritize advanced, more environmentally friendly options [76,77]. As a result, the European Union currently focuses on biofuels derived from waste and other secondary sources in its directives, as they present lower risks to food security and contribute less to deforestation and ILUC effects [78]. Moving forward, the EU will mainly support sustainable, waste-based biofuels that minimize environmental harm while maintaining energy security and environmental objectives [79]. However, in countries still interested in biofuel production and supply, the decline of first-generation biofuels tends to be slower or may not happen at all, due to persistent economic and infrastructural advantages—meaning changes are likely to be gradual or negligible (e.g., Brazil).

Unlike conventional (first-generation) biofuels, second-generation biofuels are no longer produced from food and feed crops but instead from plant by-products with high cellulose content [41,80,81]. Their main advantage over first-generation plant fuels is that they no longer interfere with food production, as they are derived from plant parts generally considered waste (e.g., corn stalks, grain straw, forestry by-

products, wood industry waste) rather than edible plants used by the food industry [82,83].

Third-generation biofuels are produced from feedstocks grown specifically for biofuel production, such as herbaceous and woody energy crops and algae [82,84,85]. Algae oil is closer to diesel oil than other vegetable oils in many aspects, including density, viscosity, and calorific value [41,86,87]. The oil yield per hectare of algae is much higher than that of existing oilseed crops, resulting in a significantly lower land requirement. This makes it the most ideal biofuel production method in terms of land use [88–91].

The fuel production process is similar to that of first- and second-generation biodiesel, but the feedstock production is highly efficient from environmental and sustainability points of view, as it uses wastewater, waste heat, and carbon dioxide. The main challenge of third-generation biofuels is the high cost of the equipment needed for their production [92,93]. Algae farming requires only small amounts of nutrients and water [94], but it also demands large quantities of CO₂ [95], intense and continuous lighting [96], and frost-free environments [97]. That's why algae used for fuel production are mainly cultivated close to power plants [98–101].

The use and sales of “clean” biofuels (E85, E100, B100) remain low because the share of FLEX (flex-fuel, FFV) internal combustion engines in the vehicle fleet (except in Brazil) is very small. The flex-fuel system allows vehicles to operate reliably on petrol, alcohol, or any combination of the two. The calorific value of bioethanol is approximately 30–35% lower [102] than that of petrol, so fuel consumption can increase by over 30% to cover the same distances (E85 vs Natural 95 gasoline) [103]. For most cars built after 2000, the limited mixing proportions (E10 and B7) do not affect vehicle operation, meaning they can be used without modifications ([104–107]). An additional benefit is that, during bioethanol production, only the starch content of plants (such as corn) is extracted, so aside from the sugar, the energy content of the remaining raw materials is conserved. Moreover, the process enriches the protein content, which is then returned to the feed chain.

3.1. Overview of the biofuel market

Globally, the U.S. leads in biofuel production, followed by Brazil. In 2023, these two countries made up over 60% of total biofuel production (Fig. 1).

It is important to note that each country's raw materials come from different crops, as varying climatic conditions affect crop yields. This is explained in more detail in subsection 3.2. Germany, a significant player in the EU, accounts for only 3.5% of global production. Additionally, the EU's four largest producers account for 8.3% of global biofuel production and nearly two-thirds of the EU's total output. Overall, the EU produces over 10% of the world's biofuel, making it the third-largest producer as a single entity. A critical interpretation of these market shares reveals that structural factors—particularly agricultural endowments, policy incentives, and blending mandates—play a decisive role in shaping the distribution of global biofuel production. Countries like the U.S. and Brazil benefit from abundant, high-yield feedstocks and long-standing blending mandates (U.S. – RFS and Brazil's E 25–27), while the EU's comparatively modest 10% share reflects stricter sustainability rules under RED III and limited agricultural endowments constrain expansion. The leading position of the United States and Brazil is largely driven by strong government support: in the U.S., mandatory blending quotas and targeted tax incentives stimulate SAF and HVO production, while in Brazil, RenovaBio's CBIO credit trading provides additional revenue that supports industry scale-up [109,110]. As a result, regional biofuel output is shaped not only by production capacity but by underlying policy frameworks and resource conditions.

The simplest way to boost production would be to expand biofuel cultivation areas. However, this conflicts with the EU's current goals, as the RED III directive aims to minimize the use of arable land for biofuel production. The Renewable Energy Directive (RED) of the EU regulates

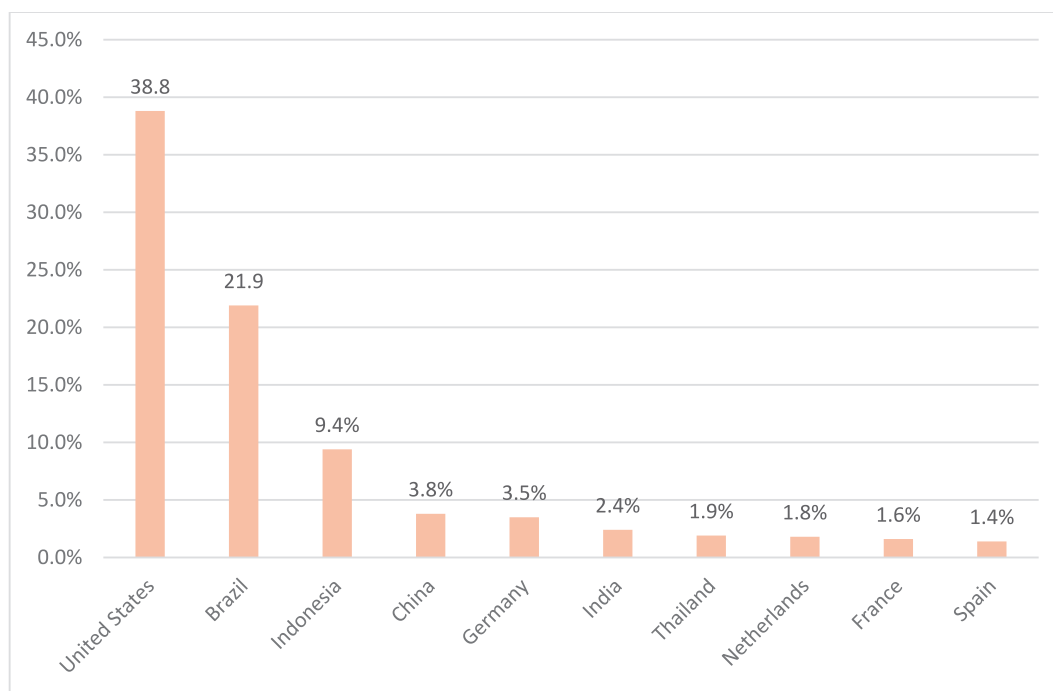


Fig. 1. Leading biofuel-producing countries worldwide in 2023, by share of global production. Source: [108].

the development of renewable energy resources, including the transport sector. The directive has been amended three times (RED I, II, III), most recently in 2023. The EU's goal is to achieve at least 42.5% of renewable energy by 2030, ideally 45%. Stricter sustainability standards for biofuels have been introduced, limiting the use of food and feed crops and reducing the risk of ILUC (land-use change). Palm oil is currently the only raw material classified as high-risk.

RED III has raised the 2030 target for advanced biofuels from 3.5% to 5.5%, encouraging fuels made from waste and residues. Transport fuel consumption is expected to decrease by 1.4% annually, the bio-content of diesel will rise from 10% to 11%, while the ethanol proportion in petrol will barely change (6.5 → 6.6%). The share of biodiesel from palm oil will drop from 18% to 3%, whereas the share produced from used cooking oil and fat will grow from 24% to 28% [111].

A new development in the EU, starting in 2020, is the mandatory adoption of E10 and B7 fuel standards, which has boosted the biofuel market. Meanwhile, due to the Russian-Ukrainian war, biofuel production in Ukraine has declined. Globally, major biofuel-producing countries like the U.S. and Brazil have also significantly expanded their production capacities, leading to an overall increase in global biofuel output. According to the IEA's Energy Model [112], demand for biofuels is projected to rise by 600 kb/d by 2030, reaching 3700 kb/d. This growth is primarily driven by government policies focused on reducing greenhouse gas emissions, cutting oil imports, and supporting domestic agriculture. The model predicts that between 2023 and 2030, biodiesel and renewable diesel will make up 42% (260 kb/d), ethanol 35% (210 kb/d), and biojet fuel 23% (140 kb/d) of the total increase [112].

In 2023, crops were the main source of biofuel production and are expected to make up 85% of production by 2030. Meanwhile, although the role of crops in ethanol production will remain stable (plateau) between 2023 and 2030, the share of vegetable oils and residual oils (such as used cooking oil and animal fats) used for producing biodiesel, renewable diesel, and biojet fuel is expected to grow significantly by 2030 [26]. The slow adoption of new generation biofuels can therefore be expected during this period.

Global biofuel production increased by more than 8% in 2024 compared to the previous year. The United States remains the largest global producer of biofuels, holding about 37%, while the U.S., Brazil,

and Europe together account for roughly 75% of global biofuel consumption [19].

Global greenhouse gas emissions rose by 1.3%, or 665 Mt CO₂eq, in 2024, reaching a new record of 53.2 Gt CO₂eq (without Land Use, land Use Change and Forestry) (Fig. 2). Apart from the crisis years 2009 and 2020, global GHG emissions have continued their steady upward trend, driven mainly by growing fossil CO₂ emissions in emerging economies. In 2024, China, the United States, India, the EU-27, Russia and Indonesia were the largest global GHG emitters, together accounting for 61.8% of global GHG emissions. Among them, China, India, Russia and Indonesia increased their emissions relative to 2023, with Indonesia showing the largest relative rise and India the largest absolute increase [113].

According to the GHG emissions of all world countries – Report 2025 [113], only 5 of the 18 countries with the largest GHG emissions share (>1% share) managed to reduce their emissions – EU27 –1.8%, Japan –2.8%, Germany –1.6%, South Korea –0.3% — while Vietnam grew by 7.6%, Indonesia by nearly 5%, India by 3.9%, Turkey by 2.7%, South Africa by 2.6%, Saudi Arabia and Russia by 2.5%. China and the US saw modest increases of 0.8% and 0.4%, respectively. Meanwhile, global GHG emissions per capita rose by 8.4% compared to 2023 [113].

Biofuels play a significant role in mitigating greenhouse gas emissions by providing low-carbon alternatives to fossil fuels, reducing lifecycle CO₂ output, and supporting broader decarbonization strategies in the transport and energy sectors.

Globally, GHG. emissions from the transport sector increased by 79% between 1990 and 2024 (Fig. 2). In the case of maritime transport, greenhouse gas emissions increased by 87% between 1990 and 2024, while aviation—having recovered from the COVID-19 crisis—now records a 136% rise compared with 1990. At the same time, in the EU-27, greenhouse gas emissions have decreased by nearly 30% compared with the 1990 baseline—falling from 4864.277 to 3164.665 Mt CO₂-eq per year —while transport remains the only sector where such reductions have not been achieved [113].

In 2024, there was also an increase compared to 2023 (+1%), a trend that nonetheless shows signs of slowing, as 2023 registered only a 4% increase compared with 2022 [114]. At the same time significant differences exist between countries, with some showing a decreasing trend

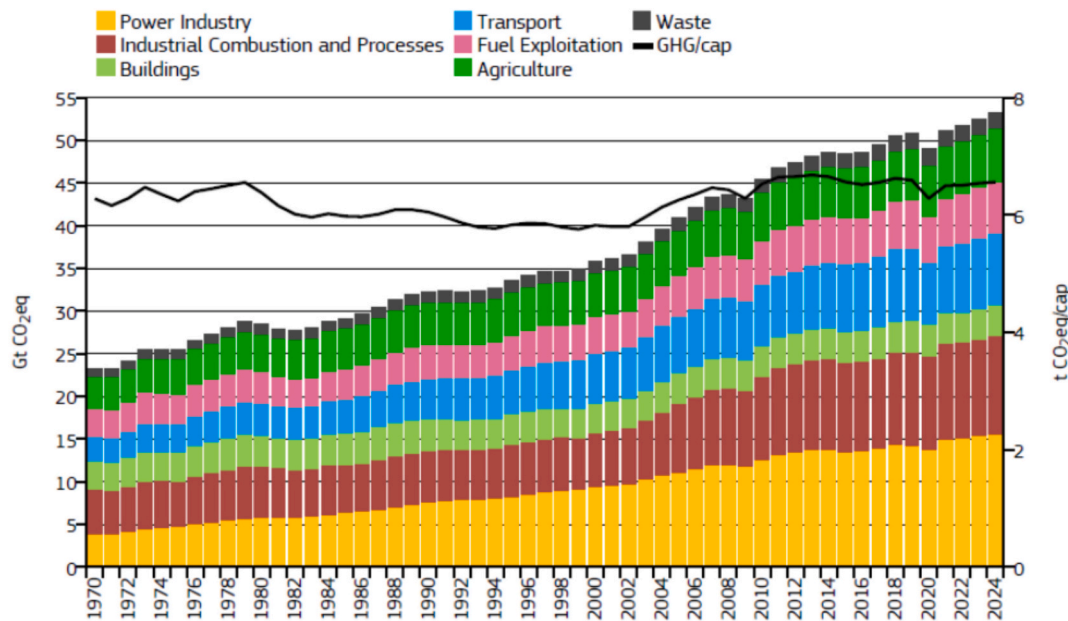


Fig. 2. Global GHG emissions by sector (left axis, bars) and per capita (right axis, black line), 1970–2024. Source: [113].

in transport-related GHG emissions [113].

3.2. Details of biofuel production concerning the raw material

According to [115] data, from 2021 to 2023, the U.S. led in ethanol production with a share of 46.9%, followed by Brazil (24.9%), China (8%), the EU (4.9%), and India (4.8%). Bioethanol was mainly produced from corn (U.S., EU, China, India), sugar crops (EU, Brazil, India), and wheat (EU, India). In terms of biodiesel production, the overall balance was more even (Fig. 3). The EU produced the most with a share of 19.2%, primarily from rapeseed oil, palm oil, and used cooking oil, followed by the USA (19.2% – soybean, used cooking oil), Indonesia (18.9% – palm oil), Brazil (11.7% – soybean, used cooking oil), and China (4.2% – used cooking oil). Biofuels are expected to expand further, with the share of advanced biofuels projected to rise by 2030, especially in the US and Europe [115], supported by regulatory policies.

According to the [117] report, the use of biodiesel (Fig. 4) and bioethanol (Fig. 5) rose sharply worldwide until 2018, then plateaued, and for ethanol, a slight decline is expected until 2030. Consumption largely

depends on the performance of the three main production regions – the U.S., the EU, and Brazil – with the share of the latter two expected to increase between 2025 and 2030.

As illustrated in Figs. 4, 5, and 6, global biofuel production experienced a temporary decline for the first time in the past decade (13.2 bln L and 1.9 bln L respectively in 2020 compared to 2019) as a result of the COVID-19 pandemic [117], a development primarily attributable to the sharp contraction of the transport sector. Because bioethanol is blended with gasoline and biodiesel with diesel, the reduction in demand for fossil fuels automatically translated into lower demand for biofuels as well. At the same time, rising corn and vegetable oil prices, combined with falling fossil fuel prices, deteriorated the economic conditions for biofuel production. This, in turn, constrained output, increased biofuel prices, and ultimately contributed to a further decline in demand [117].

In 2020, global transport fuel consumption contracted by 8.5% relative to the previous year, largely due to the mobility restrictions and extensive disruptions to trade logistics brought about by the COVID-19 pandemic. Consequently, biofuel consumption also declined, recording an 8.7% reduction compared with 2019 [117].

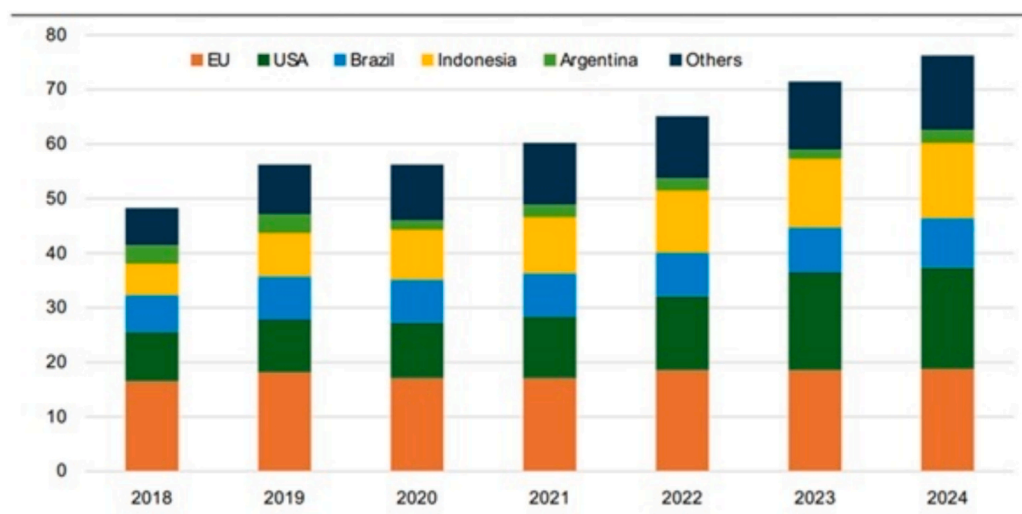


Fig. 3. World production of biodiesel rises to record level – demand for soybeans drives biodiesel fuel production in North and South America. Source: [116].

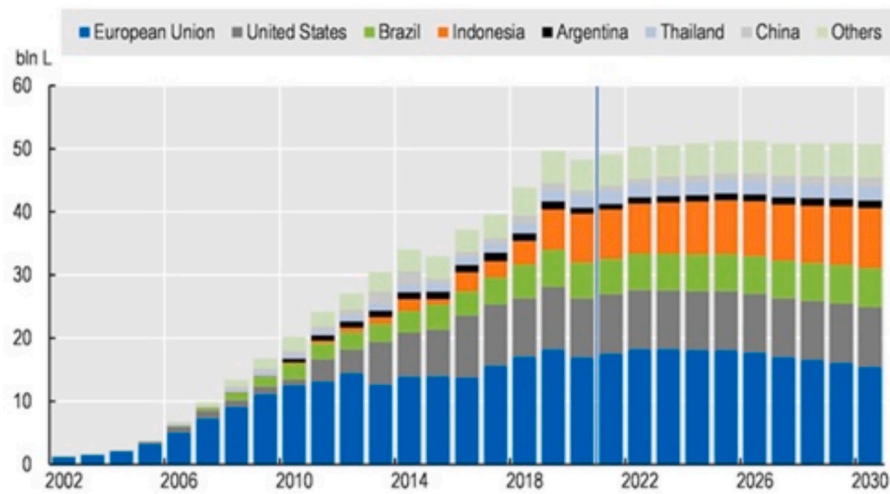


Fig. 4. Development of the world biodiesel consumption. Source: [117].

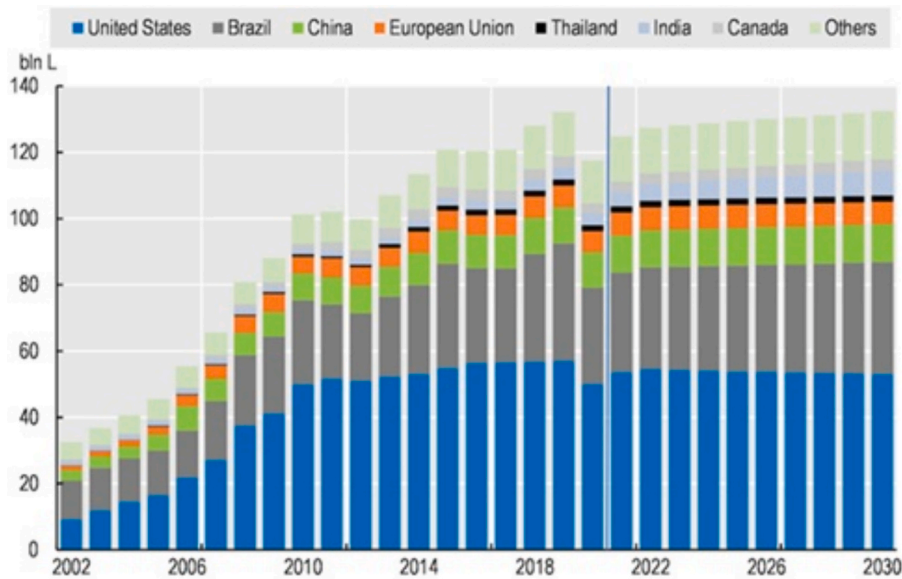


Fig. 5. Development of the world's ethanol consumption. Source: [117].

An asymmetric impact can also be observed: gasoline consumption—primarily associated with passenger transport—declined more sharply [118], resulting in a correspondingly stronger reduction in bioethanol use. By contrast, diesel demand, which is closely linked to freight transport, contracted to a lesser extent, and thus biodiesel consumption was less severely affected. Positive compensatory effects, such as increases in blending mandates, the rise in industrial ethanol use driven by its application as a sanitizer during the COVID-19 pandemic, and the use of biodiesel for power generation, were insufficient to offset the overall decline in global fuel demand. Biofuel demand returned to its 2019 level in 2021, and a slight overall increase can even be observed; however, the recovery trajectory remains uneven across fuel types. Ethanol consumption is expected to stay approximately 4% below its 2019 level in 2021 and is not anticipated to reach full recovery until 2023.

When analyzing biofuel consumption, particular attention must be paid to the choice of metrics. To obtain a deeper understanding of biofuel demand, it is essential to interpret utilised biofuels through energy-based aggregate indicators. Data expressed in thousand barrels of oil equivalent per day (kboe/d) enable cross-carrier comparisons, but they also entail certain distortions. The effects of COVID-19 on demand in

2020 materialised progressively—normal levels in the first quarter (Q1), a sharp decline from spring (Q2), and a partial rebound towards the end of the year (Q3–Q4). By contrast, energy use expressed in petajoules (PJ) constitutes an annual aggregate and is therefore more sensitive to shock dynamics. As illustrated in Fig. 6, the annual energy-use series expressed in petajoules (PJ) shows a marked decline in 2020, whereas the corresponding series calculated as an average daily flow in kboe/d does not capture this downturn and instead suggests relative stagnation. This discrepancy is attributable, first, to an averaging effect that smooths short-term, intra-year fluctuations and, second, to structural composition effects arising from the differing energy densities of biofuel types—biodiesel having a higher energy density than bioethanol—combined with the fact that the contraction in demand was more substantial for ethanol.

The results underscore that the analysis of the biofuel market is highly sensitive to the chosen metric, thus requiring methodological prudence and the explicit consideration of structural and regional heterogeneity. At the same time, it can be stated that, underpinned by strong public-policy interventions (e.g. blending obligations) aligned with economic and climate objectives, global biofuel consumption has resumed a positive trajectory, and the pandemic-related shock

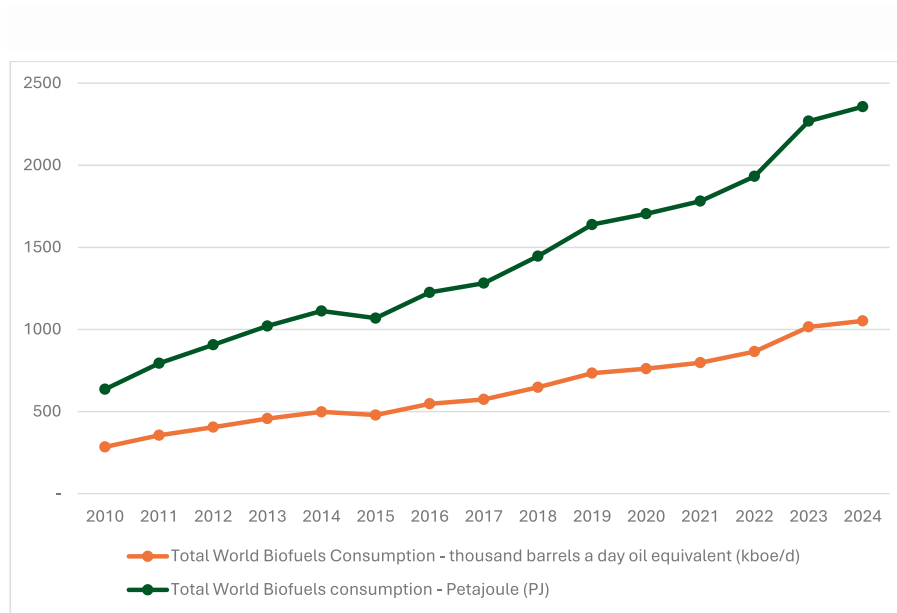


Fig. 6. Biofuel consumption. Source: [19].

dissipated within a relatively short time frame.

According to an analysis by the Agrarmarkt-Informationen-Gesellschaft (mbH) [119], various cereals, protein crops, sugar crops, fiber crops, fruits, vegetables, and more were cultivated on approximately 1.2 billion hectares in 2022. Of this, the area used for biofuel production is estimated at 6 percent. From a land-use perspective, the greatest proportion of cultivated acreage is allocated to biofuel production in the case of palm oil (30%), rapeseed (27,3%), and soybean (25,9%), while soybean and maize also stand out due to the extensive acreage devoted to their cultivation for biofuel feedstock purposes (Fig. 7). Typically, biofuels are produced in countries where there is already a surplus of suitable raw materials (mainly corn, soybean, palm oil). Biofuel production can help address surplus crop issues; it also reduces the need for fossil fuel imports and provides high-quality protein feed, which is in constant demand.

Comparing energy production on a per-hectare basis is challenging because biomass stores chemical energy—whose composition varies substantially by plant species—whereas solar and wind systems generate electricity directly. Moreover, both biomass yields and PV output exhibit wide variability depending on the cultivated crop,

environmental conditions, and the technologies employed. Typical first generation biofuel crops deliver on the order of 60–120 GJ/ha/year [120] (e.g., wheat and sugar beet–ethanol), whereas recent empirical comparisons indicate that utility scale solar PV can yield roughly can generate 20 to 100 times more energy per hectare [121].

The primary benefit of using biofuels is undoubtedly the reduction of greenhouse gas (GHG) emissions from transportation. The European Union has recognized that reaching the 2015 Paris Agreement (COP 21) emissions targets is impossible without decarbonizing the transportation sector. Transportation accounts for over 25% of the EU's greenhouse gas emissions, making emission reductions in this sector crucial for achieving the EU's climate-neutrality goal by 2050 [70]. Evaluating biofuels' impact on decarbonization requires a full life-cycle GHG analysis of energy crops to ensure an objective measure of their net emission reduction potential. Complementing broader geographic trends, life-cycle assessments (LCA) reveal significant variability across feedstock-pathways. Emissions range from ~20–35 gCO₂e/MJ for sugarcane ethanol to ~50–80 gCO₂e/MJ for oilseed-based biodiesel. Notably, waste-derived fuels and hydrotreated vegetable oils (HVO) from used cooking oil can achieve near-zero carbon intensity [26,61].

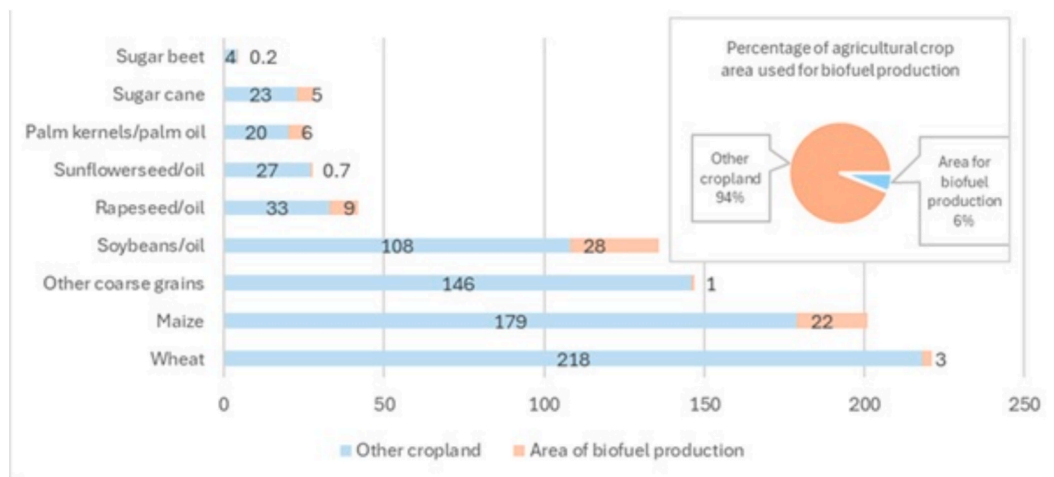


Fig. 7. Land occupied by biofuels as a proportion of total production area (in million hectares). Own editing, Data Source: [119].

Currently, there are two main options for decarbonizing transportation at the EU and global levels: promoting rapid adoption of electromobility and increasing the share of biofuels in the fuel mix. Undoubtedly, the development of electromobility has garnered significantly more attention because it is a more effective solution for reducing GHG emissions from transportation. However, as EV adoption is progressing slowly – especially in Central and Eastern Europe and Mediterranean countries [122] – the spread of electromobility is expected to take longer based on current trends. Therefore, widespread use of biofuels to meet climate goals appears inevitable.

3.3. Reservations-barriers-limits related to biofuels

The large-scale integration of biofuels into the energy system is constrained by several key factors, including *policy-driven regulatory barriers*, *economic challenges* related to cost competitiveness within the broader energy market, and *technological limitations* associated with conversion efficiency and feedstock utilization. These constraints collectively influence the viability of biofuels as a strategic component of sustainable energy transitions. According to the OECD-FAO Agricultural Outlook 2021–2030 [117], the main risks and uncertainties for the future development of the biofuels sector are related to the regulatory environment and oil prices, at the same time, production technologies fundamentally shape the scalability of these systems and, consequently, the actual contribution of biofuels to the energy mix, while the achievable conversion efficiency also plays a decisive role in determining their cost competitiveness.

Regulatory barriers.

Regulatory uncertainty includes changes in mandatory levels, enforcement mechanisms, investments in unconventional biofuel feedstocks, tax reliefs and subsidies for biofuels and fossil fuels, as well as electric vehicle (EV) technology and policies to support them. Biofuel regulations differ significantly across countries and regions, creating uncertainty for investors and producers (explained in more detail in subsection 4.1, 4.2 and 4.3). Frequent changes in subsidy schemes or biofuel mandates can further complicate long-term planning.

Since the transport sector is also responsible for significant GHG emissions, it is essential to implement targeted regulations and GHG-

reduction strategies. Globally, countries are pursuing greener transportation at various rates and are not following a uniform approach. However, developed economies often set strict targets for the period after 2030 (Fig. 8).

Countries adopt different strategies and target values to reach their greenhouse gas (GHG) emission goals (Table 2). EU Member States continue to implement biofuel blending standards to fulfill the EU's renewable energy goals, while in the U.S., the Renewable Fuel Standard establishes targets for biofuel volume (quantity). In developing economies that play an important role in biofuel production, such as India, Indonesia, and Brazil, targets are set in fixed quantities. In the case of Brazil, the RenovaBio program also includes greenhouse gas emission reduction goals [26].

The regulatory environment is not uniform; regulations differ from

Table 2
Carbon Accounting for Sustainable Biofuels. Own editing. Source: [26].

	Biofuel share (2023)	Targets
Brazil	27%	Existing: Up to 27% ethanol blending; up to 35% under discussion 2025: Up to 15% biodiesel blend 2033: 74 million carbon credit reductions in the transport sector
Canada	8%	2030: 15% reduction in carbon intensity of liquid fuel sold in Canada from 2016 baseline
China	1%	2025: 50,000 t of sustainable aviation fuel to be used between 2022 and 2025
European Union	7%	2030: 14.5% GHG intensity reduction or 29% renewable content on an energy basis (including double-counting provisions)
India	4%	2025/26: 20% ethanol blending target 2030: 5% biodiesel blending target
Indonesia	17%	2028/29: 5% compressed biogas blending target
United States	11%	2025: 35% biodiesel blending target 2025: 22.3 billion gallons of ethanol equivalent (84.4 billion litres of ethanol equivalent)
ICAO	<1%	2030: Aspiration goal of 5% CO ₂ emission reduction in aviation from using sustainable aviation fuel, lower-carbon aviation fuel, and other cleaner aviation energy resources

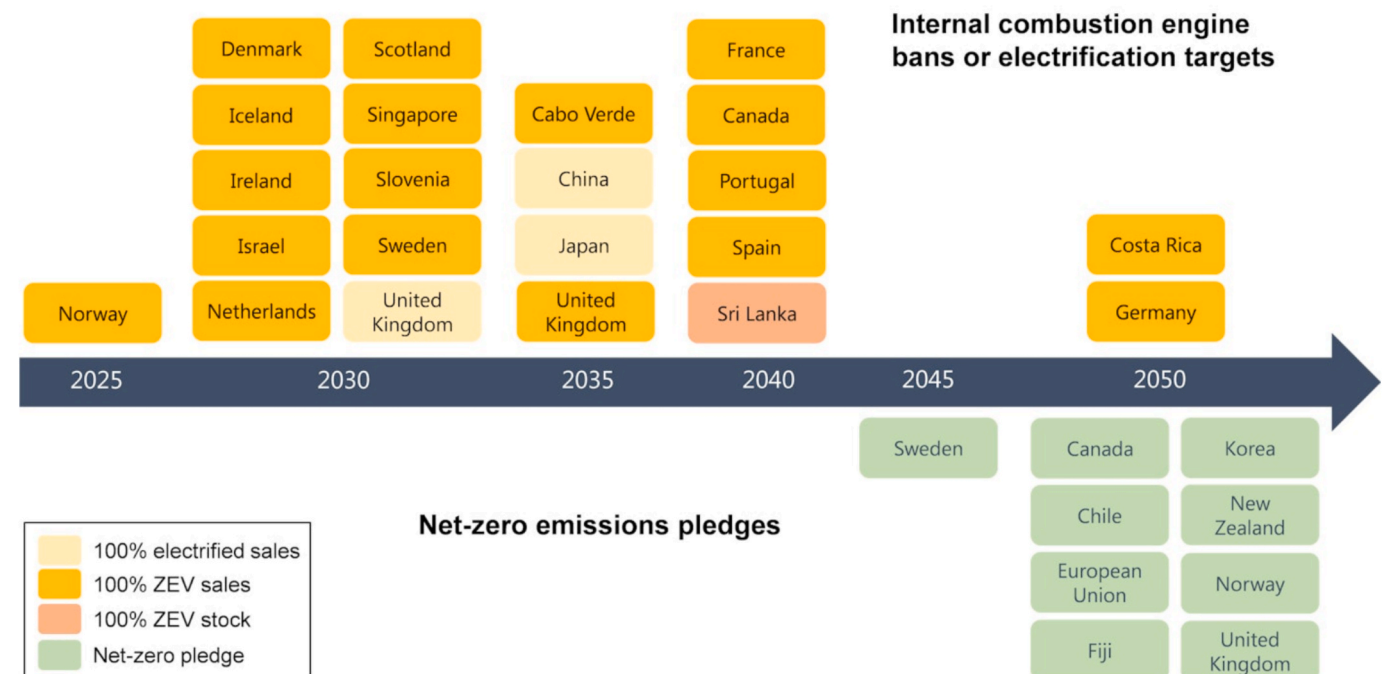


Fig. 8. Electrification targets or ICE bans for cars. Source: [123].

country to country, along with target values to be achieved. Developed countries have set particularly ambitious GHG emission reduction targets starting in 2030, and by 2050, many aim to reach “zero emissions.” The role that each country plans to give biofuels in reaching these long-term goals is an interesting question. One thing is certain: biofuels still play an important role in most countries’ 2030 targets. In countries where electromobility adoption is slower, using biofuels remains the only realistic way to cut GHG emissions by 2030.

Economic Barriers:

Biofuel production often remains more costly than fossil fuel alternatives due to expensive feedstocks, processing steps, and infrastructure needs. Market volatility in agricultural commodities also affects production stability and profitability. Since biofuels are widely regarded as substitutes for fossil-based transport fuels, a pertinent analytical question concerns the degree of co-movement between trends in global Brent crude oil prices and the evolution of biofuel consumption (demand). Understanding this relationship is essential, as fluctuations in crude oil prices may influence both the relative competitiveness of biofuels and the incentives for their deployment. As illustrated in Fig. 9 global biofuels demand has risen steadily throughout 2010–2024, reaching ~1052 kboe/d in 2024 (~2.36 EJ/year). This reflects long-running policy-driven growth (blending mandates, decarbonization targets) rather than short-term price moves.

The simple contemporaneous correlation between global biofuel consumption and Brent crude oil prices is weak and slightly negative (Pearson $R \approx -0.17$ for the period 2010–2024), indicating that biofuel demand is not strongly linked to annual fluctuations in oil prices at the global level. Episodes such as the 2015–2016 oil price collapse and the 2020 COVID-19 shock exhibit only limited responses in aggregate biofuel consumption, consistent with the predominance of mandate-driven, structurally anchored demand that dampens short-term volatility. Moreover, during 2022–2024—even in the context of elevated crude oil prices—global biofuel consumption continued to expand, underscoring the extent to which regulation-led drivers, including energy-security considerations, climate-policy objectives, and blending requirements, outweigh the influence of short-term crude price dynamics. The volatility of global crude oil prices is primarily governed by the equilibrium (or disequilibrium) between supply and demand, policy interventions (economic policy uncertainty), and geopolitical disruptions [124,125]. By contrast, biofuel markets exhibit markedly lower sensitivity to these factors, as their production costs and price dynamics are more strongly mediated by agricultural yield variability, feedstock availability, technological learning and scale effects, as well as dedicated renewable energy and environmental policy frameworks.

Technological Barriers

Large-scale conversion of biomass into fuels remains technologically complex, especially for advanced biofuels such as third and fourth-generation biofuels. Scaling laboratory-level innovations to commercial production frequently reveals efficiency and reliability challenges [126]. Technological innovation has a key role in advancing biofuel production—improving conversion efficiencies through novel catalysts, engineered biocatalysts, and process intensification—while simultaneously reducing costs and enhancing the feasibility of commercial-scale integration [127,128].

3.3.1. Food issues

In the case of the combustion of plant-based biofuels, if we disregard the emissions related to fuel production, the CO₂ absorbed from the atmosphere by plants and converted into organic matter is returned to the atmosphere during the growing seasons of the last year or years. In this approach, biofuels can be seen as a temporary CO₂ reservoir until they are used, or even considered carbon-neutral fuels. It is fair to ask, then, why biofuels do not play a larger role in the energy market?

One of the main reasons is that the total land area suitable for agriculture is limited. Expanding it can cause significant environmental damage (e.g., burning primeval forests). Additionally, newly acquired agricultural land can quickly become depleted, and its productivity may decline. Sixty years ago, about 10% of land was used for agriculture [129], and by 2021, this had increased to about 12%.

In the Southern Hemisphere, the increase in cultivated land mainly results from expanding sown areas and the adoption of modern production methods (seeds, fertilizers, plant protection, and agricultural machinery). In contrast, agricultural land is shrinking in the Northern Hemisphere [119]. Historically, the land with agricultural value has provided food for the human population for thousands of years; it also supports the production of crops needed by industry (e.g., the textile sector). As the global population continues to grow rapidly, surpassing 8 billion, it is increasing quickly. A 2024 study reports that Earth’s population is currently growing by about 200,000 people per day [130], which greatly affects food security and other critical issues.

According to a report by [131], approximately 733 million people went hungry in 2023, affecting one in eleven people worldwide and one in five in Africa. If the current trend continues, approximately 582 million people will be chronically malnourished by 2030, half of whom will be in Africa.

According to a report by the [132], the world faces a “food deficit” of about 70%, taking into account the amount of vegetable calories available in 2006 and the calories needed by 2050, assuming that the market penetration of biofuels globally would not significantly exceed the current share of 2.5%. And setting higher biofuel targets (at least

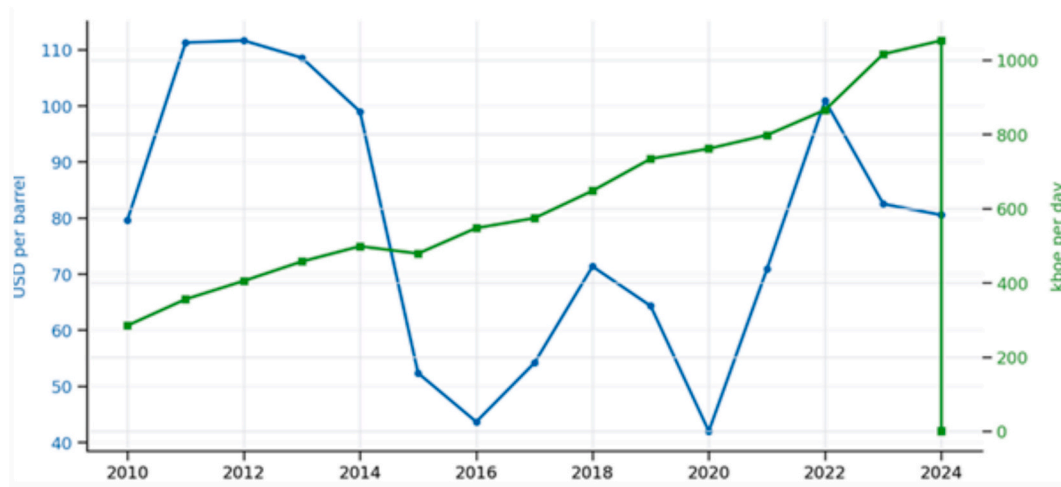


Fig. 9. Relationship between the global average crude oil price and the demand for biofuels. Source: Biofuels demand (kboe/d): [19]. Brent price (USD/bbl): [124].

10% of transport fuel by 2020) could increase this food shortage to up to 90%.

Achieving a 20% contribution of bioenergy to global energy demand by 2050 would likely require, at minimum, a doubling of annual plant-based biomass production across pathways. Such a scale-up would pose significant feasibility and sustainability constraints. Therefore, it is especially important for the EU to now limit the share of food-based biofuels in the RED III Directive, even if the targets set in the directive are not primarily aimed at fighting hunger but rather at protecting biodiversity and reducing GHG emissions.

Since the predictable food supply for the world's population has not been resolved despite the UN-FAO's efforts, and considering the expected demographic changes, as well as the negative effects of climate change, there will be increasing pressure and focus on agriculture, food supply, and food security. In this context, it is not feasible to fully replace traditional fossil fuels with biofuels, as producing them would require cultivating large areas of land for energy production.

Additionally, as the world population grows, so do mobility and transportation needs. Due to economic development and rising standards of living in African and Far Eastern countries, levels of motorization, mobility demands, and opportunities for the population are also expected to increase. As a result, there is growing pressure on both food production and transportation systems. Given all this, large-scale biofuel production, which could potentially replace current fuels entirely, cannot be considered a viable option from an economic, technical, environmental, or moral perspective.

3.3.2. The ILUC problem

The environmental impact of biofuel production and use is also highly controversial. Some manufacturing processes produce more greenhouse gases than conventional fossil fuels. First-generation biofuels are typically grown in large-scale monocultures, which reduces biodiversity, can cause soil degradation, and takes land away from crops grown for food. Changes in vegetation for cultivating raw materials (e.g., palm oil) can decrease atmospheric CO₂ absorption by natural vegetation (e.g., the expansion of palm oil plantations at the expense of rainforests). The core issue of the indirect land-use change (ILUC) impacts of biofuels is that untouched areas are cleared as the biofuel industry expands to grow more crops for biofuel. Overall, ILUC increases greenhouse gas emissions and also leads to significant social and environmental impacts affecting biodiversity, water quality, soil quality, food prices and supply, land rights, worker migration, and community and cultural stability. ILUC emissions vary greatly depending on the feedstock, especially for sugarcane, palm oil, and soybeans. Advanced biofuels have a much lower ILUC risk. Regarding biodiversity, there is a risk that biodiesel and bioethanol feedstock production in developing countries will occur in areas that provide vital ecosystem services [133]. Additionally, from an energy perspective, producing crops for fuel is actually a low-energy-efficient use of arable land, since modern solar systems can now generate more than 100 times the useful energy per hectare compared to what bioenergy is likely to produce in the future [132]. That is why we need to develop more sustainable production methods and responsibly produce raw materials.

According to Article 3 of the European Union Directive 2015/1513 [134] of 9th September 2015, the European Commission is required to provide information and analysis of the available and best available scientific research results and evidence on ILUC emissions related to the production of biofuels across all processes. A report summarizing over 300 sources of literature [135] on ILUC emissions shows that the results vary significantly due to differences in parameters used and considered. It notes that further targeted research is necessary to better understand and model the ILUC phenomenon, but certification of low-ILUC-risk biofuels (as defined in Directive 2015/1513/EU) is feasible. Reported ILUC emissions vary widely in the literature, reflecting strong dependence on the feedstock used, the modelling framework applied (e.g., GTAP-BIO, MIRAGE, CGE-based approaches), and the assumed

amortization period. ILUC emissions exhibit extremely high variability across feedstocks, ranging from negative values (≈ -100 gCO₂e/MJ) for lignocellulosic pathways to several hundred or even >1000 gCO₂e/MJ [136] for certain oil-based biodiesel pathways, while policy frameworks such as the EU RED typically apply standardized values in the range of 4–66 gCO₂e/MJ [134]. Feedstocks with low ILUC risk, particularly forestry or agricultural waste, and crops specifically grown for energy, appear to be promising options. Nevertheless, additional measures are required, such as integrated land-use planning that also safeguards natural vegetation. Sustainability certification schemes can reduce direct deforestation at the plot level, particularly in high-risk commodities such as palm oil (e.g., RSPO certification reduced deforestation by $\sim 33\%$ in Indonesian plantations) [137], however, their aggregate effectiveness remains limited due to leakage, selective adoption, and insufficient enforcement, which prevent substantial reductions in overall deforestation rates [138].

The previous ILUC Directive is now part of the RED III Directive, which is a more stringent update of the earlier (RED II) Directive. More rigorous sustainability standards have been put in place to limit the use of food and feed crops and reduce the risk of ILUC (indirect land-use change).

The tightening of the ILUC regulation aims to reduce unintended greenhouse gas (GHG) emissions that can happen when land used for food or feed production is converted to grow biofuel crops, which could lead to deforestation or the conversion of other valuable areas.

An important part of the regulation concerns the upper limit on biofuels with a high ILUC risk, which restricts their use at the consumption level in 2019. The specified ceiling is intended to be gradually decreased from 31st December 2023 until it reaches 0% by 31st December 2030.

At the same time, the Directive encourages the production and use of low-ILUC-risk fuels. To accomplish this, advanced biofuels (such as those made from waste, residues, algae, or straw) will be given targeted incentives and specific milestones.

At the EU level, all biofuels produced must meet stricter mandatory sustainability and GHG emission-reduction criteria. They are expected to achieve at least 80% GHG savings compared to fossil fuels. The purpose of the rules related to the RED III regulation is to ensure a smooth transition toward truly sustainable, low-emission renewable energy resources in the transport sector, thereby helping to meet the EU's climate goals.

4. Expected development

Given all this, it is no surprise that more countries worldwide are taking targeted steps to promote advanced biofuels, as it is clear that increasing first-generation biofuel production is concerning due to limited land, food issues, and the ILUC problem. In the United States, the Renewable Fuel Standard (RFS) has already set goals to boost the share of cellulosic and advanced biofuels and to cut GHG emissions (Table 3). In Brazil, GHG reduction is also a priority, but here the focus is generally on biofuels produced, aiming to implement more sustainable practices

Table 3

Biofuel GHG reduction requirements in selected policy frameworks. Own editing. Source: [26].

GHG reduction thresholds	
United States (RFS)	20% reduction in conventional biofuels compared with fossil fuels, 50% for advanced fuels, and 60% for cellulosic biofuels
Brazil	Specific annual GHG reduction 2024 target: 16–17% reduction; 2033 target: 25% reduction
European Union (RED III)	50% reduction compared with fossil fuels when operational before 2015, 60% when starting operations in 2015–2020, 65% in or after 2021
India	No specific GHG requirements
CORSIA	10% reduction compared with fossil fuels

across the entire life cycle (including crop production, harvesting, transport, and biofuel manufacturing). The current EU directive, RED III, targets achieving a 5.5% share of advanced biofuels by 2030, while also setting GHG reduction targets for all biofuels.

These three countries are the top three biofuel producers, so their actions will significantly influence the future development of biofuels. That is why we considered it important to examine these countries in more detail. In the following sub-chapters, we discuss the biofuel market in Brazil, the U.S., and the EU.

4.1. Brazil and flex-fuel vehicles

Brazil is the leading biofuel producer in South America and the second-largest globally [139,140]. In Brazil, soy is the main feedstock for biodiesel, but castor, sesame, sunflower, and oil palm are also important sources [141,142]. Ethanol production has traditionally dominated the country, but biodiesel has also seen significant growth. In 2019, Brazil produced 5.9 million cubic metres of B100 biodiesel; 6.44 million cubic metres in 2020; 6.76 million cubic metres in 2021; and 6.25 million cubic metres in 2022, tripling renewable fuel production in the past decade [143,144]. Brazil's flex-fuel vehicle fleet offers a strong market for large-scale biofuels. A key question is whether Brazil will sustain long-term, sustainable transportation through biofuels or follow global trends by adopting electromobility.

4.1.1. Biofuel conditions in Brazil

Brazil is a major player in the global biofuel industry: longstanding government programs (Proálcool), a high-performing sugarcane-based ethanol sector, and flexible technology (flex-fuel) supporting the vehicle fleet have enabled the country to connect its domestic fuel supply with climate policy goals [140,145,146]. Recent policy decisions (RenovaBio; 2025 E30/B15 blended fuel mandate) further bolster biofuel efforts, while increasing corn-based ethanol and biodiesel production, sugar/ethanol allocation choices, and the growing but still limited adoption of electromobility create a complex transition [147–149].

Brazil is one of the world's leading producers of biofuels; most of its ethanol comes from sugarcane, which is highly efficient feedstock due to its tropical climate, high solar radiation, and high yields [150]. The combination of the industrial efficiency (high t/ha) of Brazilian sugarcane cultivation and advanced refining and fermentation technologies results in high ethanol yields per hectare – for this reason, sugarcane ethanol (litres/ha) demonstrates statistically better area efficiency compared to many temperate crops [148,151].

Brazil's biofuel production is supported by various government programs, all of which have helped advance the significant role of ethanol and biodiesel production in the country's transportation sector.

Proálcool (Pró-Álcool, 1975): the first typical government-run fuel conversion program in Brazil. The goal was to reduce dependence on oil imports, and this laid the foundation for the sugarcane ethanol industry [147,152,153].

PNPB – Programa Nacional de Produção e Uso do Biodiesel (2004): The Biodiesel program focused on rural employment, engaging smallholders, and gradually implementing diesel blending targets [154,155].

RenovaBio (2017, Law No. 13.576/2017): A modern, market-driven biofuel policy that ranks biofuel producers by their carbon intensity and encourages them with a decarbonization credit (CBIO) system. RenovaBio standardizes the GHG performance of biofuels and assigns capital market value to carbon savings. The program represents a policy innovation that combines lifecycle emissions accounting with a tradable credit mechanism. The program aims to reduce GHG emissions while promoting efficiency improvements in biofuel production. RenovaBio establishes national decarbonization targets expressed in CBIO units (1 CBIO = 1 ton of CO₂-equivalent emissions avoided). The targets at the macro level, for the next decade are to avoid approximately 600 million CBIO, and to reduce the carbon intensity of transport fuels by

approximately 12% by 2035 [156,157].

Policy changes for 2024–2025: E30 and B15: In mid-2025, Brazilian energy policymakers approved increases in fuel blending rates: the proportion of hydrogenated ethanol in gasoline was raised from 27% to 30% (E30), and biodiesel blending went from 14% to 15% (B15), effective from 1st August 2025. The decision aims to reduce import dependency and support the domestic biofuel industry. The rapid growth of corn-ethanol contributed to this change, making it possible to meet the increased demand [158–160].

Besides government decisions, shifts in market factors also greatly influence biofuel production. Each season, Brazilian mills determine the percentage of harvested sugarcane to turn into sugar and the percentage to ferment into ethanol. This ratio depends heavily on global sugar prices and local fuel pricing policies. Usually, a one-percent change has a significant impact on exports and the domestic market, as the volumes involved are very large [161–163].

In recent years, high sugar prices have led to more sugarcane being converted into sugar, with less ethanol being produced from sugarcane. Meanwhile, the role of corn-based ethanol has increased to fill the gap in the fuel market. In 2024–2025, Brazil experienced the rapid expansion of corn-ethanol production [160]. Overall, if the global market price of sugarcane were higher and sugar was produced from sugarcane, the missing bioethanol could be produced from corn – allowing the Brazilian ethanol industry to diversify its sources.

4.1.2. Flex-fuel technology: how it works and why it matters in Brazil?

The fuel system of flex-fuel (FFV) vehicles includes corrosion-resistant materials, modified injectors and pumps, and an engine control unit (ECU). These components are essential for using any ethanol blend (0–100%). Many systems incorporate an inline ethanol composition sensor. However, one of the key developments in Brazil was the Software Fuel Sensor approach, where the ECU determines the mixture ratio from the lambda probe and existing sensors (making it more affordable and compatible with mass production) [164].

The Brazilian version of the flexible technology has been a commercial success: the market share of “flex” cars in local sales has been consistently high for many years [165]. Since the mid-2000 s, most new vehicles have been equipped with flex capability. According to data from 2024, approximately 79–90% of new sales consisted of flex vehicles [166]. This widespread adoption, along with the 33,000+ filling stations with ethanol infrastructure, has made ethanol a truly viable alternative [167].

Globally, the adoption of electric cars is evident, but in Brazil, local factors such as the widespread use of bioethanol and FFVs have slowed the adoption of electromobility. Car manufacturers (e.g., Toyota, GM, Stellantis) have introduced hybrid-flex and plug-in flex concepts that combine an electric drive with an ethanol-compatible internal combustion engine; therefore, this is a regional trend, not necessarily a global one. These developments should be viewed in the context of local fuel supply and climate goals [168].

Although biofuels remain the most common alternative fuel for transportation in Brazil – contrary to global trends – electromobility is also starting to gain ground in the country. Sales of electric vehicles (BEV) and plug-in hybrids are rising rapidly, but their share of the total vehicle fleet remains very low (for example, in 2024, EV shares in new car sales were about 1–3%; flex-fuel continues to be the leading category in new car sales in 2024) [169].

Using renewable energy resources as fuel is a key part of sustainable transportation. For electric vehicles, the fuel is electricity, so the environmental impact depends on the energy mix of the power grid [170]. Brazil's electricity grid has a significant (and growing) share of renewables, mainly hydropower + rapidly expanding wind and solar power. This means that the lifecycle emissions of EVs can be relatively low; at the same time, the decarbonization of transportation in Brazil relies not only on EV adoption but also on how transport-oriented energy policies (e.g., E30/B15, RenovaBio) influence short- and medium-term outcomes

[171,172].

Flex-fuel and hybrid-flex approaches (combined with locally produced ethanol) could serve as a more affordable and politically appealing solution in the short to medium term for reducing CO₂ emissions in a large, developing country. Meanwhile, in the long term, electric propulsion powered by recycled or renewable electricity remains a crucial alternative for transportation. These two options are not necessarily mutually exclusive; the main question is which time frame and political strategies will be used to manage the transition [173].

4.1.3. Brazil's competitive advantage: The primary reason for the widespread adoption of biofuels

Below is a brief comparative overview of the typical litres/hectare/year ranges for different biofuel feedstocks. Figures can vary significantly by region and production method. The following are the ranges commonly cited in the literature:

- **Sugarcane (Brazil, ethanol):** typical average 6000–7500 L ethanol/ha/year; industrial conversion factor approximately 80–85 L ethanol/ton of sugarcane. Some models and advanced practices also mention a potential of over 9000 L/ha [174–176].
- **Maize (corn-ethanol, USA/Brazil):** typical 2000–3500 L ethanol/ha/year (highly dependent on yield and technology) [176–178].
- **Sugar beet (EU, sugar beet ethanol):** variable; typically medium range (a few thousand L/ha) – depending on the region [179]. According to [180], the average is 5250 L ethanol/ha/year, according to [181], 5000 L ethanol/ha/year, but under ideal climatic conditions, it can reach up to 11000 L/ha/year.
- **Oil seed crops (biodiesel):**
 - o **Palm oil (Malaysia/Indonesia):** high oil yield in → biodiesel approx. 3500 to 5700 L oil/ha/year [182,183].
 - o **Rapeseed/canola (EU):** approximately 1000–1500 L/ha/year of oil (generally much less than palm oil) [175].
 - o **Soybean (USA/Brazil):** lower oil yield, typically a few hundred litres of oil/ha/year [160,184]. According to [182], it is one-tenth of the palm oil yield.

Thanks to the high sugarcane yields driven by Brazil's tropical climate and advanced industrial efficiency, the country has one of the best “litres of biofuel per ha” indicators (especially on the ethanol line). This gives Brazil a comparative advantage over other nations where colder climates and seasonal limitations reduce yields. That is why biofuels are currently a practical alternative in Brazil, enabling the country's transportation sector to run primarily on biofuels for an extended period and helping to meet decarbonization goals.

In conclusion, Brazil's strengths include high territorial efficiency (sugarcane), advanced industrial expertise, a widespread flex-fuel vehicle fleet, and RenovaBio's market-oriented incentives. Collectively, these factors will allow Brazil to increase its biofuel consumption (E30/B15) in the short and medium term, reduce its fuel imports, and contribute to decarbonization goals—mainly through domestically produced ethanol.

At the same time, the currently viable Brazilian model also has its limitations and risks, which is why government decisions are especially important in shaping future trends.

1. **Food/energy allocation:** the sugarcane industry's decision to produce sugar or ethanol is sensitive to world market prices; large reallocation could lead to food price effects in the short term [140,185,186].
2. **Environmental risks:** ILUC (indirect land-use change), biodiversity loss, fertiliser/water use – these can be mitigated by mechanisms for monitoring RenovaBio and good practices.
3. **Technology transition and EV competition:** although the sales of electric vehicles are growing rapidly, their share of the total vehicle

stock remains low; therefore, in the short to medium term, biofuels will continue to play a vital role in decarbonization in Brazil [166].

Brazil's competitive advantage – high sugarcane yields, decades of industry experience, and a nationwide fleet of flex-fuel vehicles – provides a strong foundation for short- to medium-term goals of energy independence and transport decarbonization. Meanwhile, sustainability, land-use management, and coordination of the technological transition are vital to ensuring that the growing use of biofuels remains truly climate-friendly and socially acceptable.

Brazil's current biofuel regulatory framework – centered on the RenovaBio program – has significantly advanced transport decarbonization, yet it also entails notable policy stability and sustainability risks. A key concern is regulatory uncertainty, as periodic revisions of decarbonization targets (CBIO quotas) and political influence over fuel pricing and blending mandates may weaken long-term investor confidence. From a sustainability perspective, ILUC remains a structural risk, especially given the expansion of soybean-based biodiesel and sugarcane ethanol, which may contribute to deforestation. Finally, a broader systematic risk lies in technological lock-in, where continued policy preference for biofuels could slow the adoption of electrification pathways, particularly in light-duty transport. Taken together, Brazil's regulatory framework is innovative and performance-oriented, at the same time its long-term sustainability will depend on enhancing regulatory predictability, improving environmental safeguards, and ensuring balanced integration with emerging low-carbon transport technologies such as electric mobility and advanced fuels.

4.2. Biofuel landscape in the United States

The biofuel industry in the U.S. has expanded largely due to incentives based on the Renewable Fuel Standard (RFS) [187] framework and periodic tax/blender credits since the mid-2000 s [188,189]. Conventional ethanol (corn-based) remains the most significant biofuel in terms of quantity, while recent investments and regulatory pressures have mainly focused on increasing production of renewable diesel, and sustainable aviation fuel (SAF) [190,191]. The yield-boosting and cost-cutting effects of GMO crops (mainly maize) have helped supply feed and industrial feedstock, but debates over sustainability and ILUC (indirect land-use change) continue to influence upcoming government decisions [192,193].

Basically, ethanol remains the dominant biofuel in the U.S. Ethanol production was around 15 to 17 billion gallons per year in the 2010 s. It was ~15.4 billion gallons around 2022, with capacity increasing in 2023 [194–196]. In addition to ethanol, biodiesel and renewable diesel are becoming increasingly important, as from the end of the 2010s and especially between 2020 and 2024, a strong wave of investments began in the production of renewable diesel (more specifically, hydrotreated vegetable oil – HVO – and waste-to-hydrocarbons type diesel). By 2023, the share of both renewable diesel and biomass-based diesel (i.e., conventional, plant-based biodiesel and renewable diesel combined) has increased significantly [197,198]. In addition to road transportation, renewable energy resources, including biofuels, are becoming increasingly important in aviation. Sustainable aviation fuel has begun to grow rapidly since 2023 [199,200]. According to short-term forecasts [201], both SAF and waste-based fuels are expected to expand significantly as more plants and business agreements have been established or will be soon.

In the United States, GMO corn plays a major role in biofuel production as the primary source for ethanol, while soybeans also play an important part. The spread of GMO corn and soybeans has led to increased yields per hectare and lower cultivation costs (such as reduced pesticide use and less operational labour), which indirectly provides cheaper feedstock for the biofuel industry [202]. Some studies have shown that the adoption of biotech varieties has contributed to a rise in maize intensity in the Corn Belt region [203,204]. At the same time, as

mentioned earlier, more investments are being made to support the production and the distribution of SAF and renewable diesel [128,205]. All these developments will likely reduce the production of traditional corn-ethanol over time due to the previously mentioned ILUC effects and ongoing sustainability concerns.

The U.S. biofuel sector has been a politically driven (RFS) industry since the 2000 s; most new incentives and investments in recent years have shifted from conventional ethanol to higher-energy-density, waste- and fat-based renewable diesel and SAF [199]. Although the spread of GMO crops has helped make corn-ethanol more competitive through increased crop yields, it now seems that the next major breakthrough in alternative fuels could be the industrialization of cellulosic/SAF technologies and waste feedstocks — provided production costs, sustainability factors, and the right regulatory framework are all optimal. The transition is likely to be a long process, given that U.S. corn-ethanol plays a significant role globally, so stopping it abruptly could cause major disruptions in the worldwide biofuel supply [206].

4.3. Biofuels in the EU

Over the past decade, the EU's biofuels policy has shifted toward a highly regulated, goal-driven approach, emphasizing reductions in fossil fuel emissions, enforcing sustainability standards, and, especially in recent years, encouraging sustainable aviation fuel (SAF). The Renewable Energy Directive (RED II → RED III) (2023/2413/EU) and the ReFuelEU Aviation legislation (2023/2405/EU) [207] primarily influence demand and acceptable feedstocks; the EU is restricting the growth of food-based biofuel blending while speeding up the promotion of waste and advanced (non-food-based) solutions [208].

Following the 2018 RED II framework, RED III in 2023 further tightened the 2030 targets and the sustainability criteria for bioenergy, including ILUC risks. The RED III Directive anticipated an increase in the share of advanced biofuels in transportation energy use. Additionally, as outlined in the “Fit for 55” climate package [209], the EU aims to significantly lower its emissions by 2030, and ReFuelEU Aviation (EU) 2023/2405 mandates a compulsory increase in the share of SAF in air traffic—thus, like the US, the EU is also working to reduce aviation emissions.

According to the ReFuelEU regulations, SAF must hold a 2% share in 2025, and this mandatory share will then be gradually increased each year. The EU is working to reduce the portion of food-based biofuels (which carry high ILUC risk) through current directives, while continuing to require the production of advanced biofuels. Meanwhile, the 2035 goal is to ban the registration of cars with internal combustion engines, signaling a gradual decline in the role of biofuels in road transportation.

In recent years, the EU's policy has been to restrict food-based biofuels. The EU is intentionally delaying the promotion of high-ILUC-risk vegetable oils and certain food-based biofuels, favouring waste and advanced feedstocks [210]. However, these are much more expensive than using fossil fuels [211]. There is still considerable debate about the sustainability of biofuels [78,127], which means relevant regulations may change soon. Meanwhile, the market for electric vehicles is steadily growing each year, potentially influencing future biofuel regulations.

Currently, the EU is increasingly promoting waste-to-fuel technologies and the use of renewable diesel in the fuel market (ReFuelEU, Fit for 55, RED III). More countries (such as Sweden and Finland) are expanding their capacity to produce and utilize hydrogenated vegetable oil (HVO) — we will discuss Sweden's HVO program further in the next subchapter. At the same time, it is important to recognize that waste-to-fuel technologies are currently unable to replace the first-generation biofuels lost due to regulations, because of the limited availability of feedstock [212].

The cost and scale of feedstocks produced in global markets (e.g., Indonesia/Malaysia oil palm, Brazil sugarcane ethanol, North American GMO corn) are often lower than production costs within the EU —

especially when production relies on more advanced cultivation (GMO) techniques, efficiency from larger scales, and cheaper labour/growing conditions [213–215]. This puts the EU at a disadvantage in biofuel production. It is no surprise that the EU imports a significant amount of ethanol from the U.S. and Brazil.

The global and European electrification trends are supported by several forecasts, including the [216]: the spread of electric transportation (increases in EV sales, network investments, and battery production) will fundamentally decrease long-term demand for liquid fuels, especially those burned in passenger cars. [216–218]. In the EU, legislation (e.g., Fit-for-55 directives, vehicle emission standards, and national incentives) is reinforcing this trend.

As the passenger car fleet becomes increasingly electric, the demand for car-focused biofuels (onshore petrol/diesel) is declining. This is especially critical for corn-ethanol and conventional biodiesel, which have historically supplied a significant portion of the road fuel market. The increase in electromobility (both in the EU and worldwide) will lead to the largest drop in demand for traditional road biofuels, resulting in a long-term reduction in the volume of companies affected.

The EU biofuels market will remain a key part of the decarbonization toolkit in the short to medium term, especially as a SAF in aviation. However, a mix of structural factors — such as cheaper feedstocks from external markets (GMO-corn, oil palm, sugarcane), EU legislation and ILUC policies that limit first-generation biofuels, and the rapid growth of electromobility — will exert a strong downward but non-linear influence on biofuel volumes and overall demand growth. Meanwhile, waste- and by-product-based technologies (e.g., renewable diesel, waste-to-fuel, and SAF production) could help mitigate declines in some countries, especially Sweden and Finland, but may not fully counteract trends driven by international competition and electromobility.

Overall, two main trends are likely to emerge in the EU's alternative fuels industry. On the one hand, regulations (RED III, ReFuelEU, ILUC requirements), the growing adoption of electromobility, and cheaper biofuels (e.g., corn-ethanol and HVO) available outside the EU are increasingly negatively impacting biofuel production within the EU, particularly for first-generation biofuels. As a result, a decline in conventional biofuel production is anticipated. On the other hand, due to regulatory systems and sustainability considerations, a significant increase in the production and use of waste-based “advanced biofuels” (HVO, waste-to-fuel, SAF) is likely. These products can offer a particularly sustainable way of driving, as their raw materials are actually “products” labelled as waste. Therefore, they may be able to offset the decline in the volume of conventional biofuels, but only partially.

4.3.1. Biofuel production in Sweden and the role of HVO

Sweden is one of the leading member states of the European Union in using renewable energy resources for transportation. The country's energy policy aligns closely with the EU's Renewable Energy Directive 2009/28/EC (RED I) and its amendments (RED II, 2018/2001/EU; RED III, 2023/2413/EU), as well as the ‘Fit for 55’ package. Sweden aims to reach climate neutrality by 2045, with a key focus on decarbonizing the transportation sector. Hydrogenated vegetable oil (HVO) plays an important role in this effort, demonstrating a more favourable environmental performance than conventional biodiesel [219,220].

HVO is a biofuel produced by hydrogenation from various lipid sources (animal fats, vegetable oils, used cooking oil) [221]. During the process, triglycerides and free fatty acids are hydrogenated, yielding a paraffinic fuel free of sulphur and oxygen [222]. The great advantages of HVO are its high cetane number, full compatibility with fossil diesel engines, and low emission profile [223].

In Sweden, the use of animal fats and used cooking oil (UCO) is particularly emphatic. These are second-generation biofuels, produced in a way that does not directly compete with food production, unlike first-generation biofuels, such as rapeseed or palm oil [224]. This aligns with the EU's sustainability criteria, especially the regulations for reducing ILUC (Indirect Land Use Change) risk [225].

In Sweden, HVO makes up approximately 70–80% of biofuel consumption [26]. The country has several major industrial players in this sector, such as:

- **Preem AB** – The largest oil refinery in Sweden that distributes HVO-based diesel substitute under the name HVO100.
- **Neste (centre in Finland but with a strong market presence in Sweden as well)** – one of the largest HVO producers in the world, producing HVO from UCO and animal fats.

Public policy promotes biofuel use through strong incentives: tax benefits, quota obligations, and targeted subsidies [226–228]. As a result, GHG emissions from Sweden's transport sector have decreased by 26.1% thanks to biofuel use [229], making it one of the highest reduction rates in the EU.

In Sweden, the use of HVO has a notable sustainability impact in several ways. It helps reduce GHG emissions, as HVO made from used cooking oil and animal fats can cut emissions by up to 90% compared to conventional diesel, according to RED III. Using UCO (used cooking oil) and animal by-products promotes waste recycling and resource efficiency, supporting the circular economy. Additionally, HVO raw materials help reduce the conflict between land use and food security, which is the most debated issue associated with first-generation biofuels.

At the same time, a critical approach is justified, as there are limiting factors and potential sustainability risks associated with the use of HVO. The supply of animal fats is limited, leaving the available raw material insufficient to offset the shortage caused by the reduction in first-generation biofuels. Additionally, the global UCO trade presents sustainability risks, since, for example, the inclusion of palm oil in UCO shipments violates rules in several ways [230,231].

The EU policy framework is increasingly encouraging member states to adopt electromobility, but biofuels, especially those produced from second-generation resources, continue to play a vital role during the transition period. Sweden serves as a model in this context: while expanding its electric vehicle infrastructure at an extremely rapid rate (almost 60% of new car sales in 2024 were electric or plug-in hybrids), it is also making immediate GHG reductions within its existing internal combustion engine fleet through widespread use of HVO. Therefore, further strengthening of electromobility is expected, particularly in the passenger car segment, along with maintaining the role of HVO and other advanced biofuels. This strategy will allow Sweden to adopt a flexible and technologically diverse approach to decarbonizing transportation. This transitional dual approach aligns fully with the EU's 2030 climate goals and the RED III objective of achieving a 29% share of renewable energy in transportation.

5. Additional research directions

There are numerous opportunities for further research and exploration to better understand the role, sustainability, and future potential of biofuels, as well as to develop more efficient, environmentally friendly, and economically sustainable solutions for decarbonizing the transportation sector.

A primary research direction could be to further refine and expand the comprehensive life cycle assessment (LCA) of biofuels, especially to better model ILUC risks. Currently, there is considerable variation in the results, so it is essential to develop complex, multidimensional models that consider global land-use changes, biodiversity impacts, and energy and resource-efficiency indicators. This approach will help identify and promote sustainable biofuel activities, particularly those involving low-ILUC-risk feedstocks.

Further research directions could include developing and applying high-yield, sustainable feedstocks, such as the targeted cultivation of third-generation biofuels like algae and other microorganisms. Improving the efficiency of these technologies, lowering production costs, and building infrastructure are essential steps for expanding

markets and enhancing energy independence. Additionally, the widespread use of innovative, waste-based feedstocks that do not compete with food production and have a lower environmental impact could become a key area of research.

Furthermore, it is important to continue international comparative analyses, especially regarding the impact of the biofuel policies of different countries, the application of sustainability criteria, and their effectiveness. This can help identify best practices and develop global regulatory frameworks that support sustainable development while minimizing social and environmental risks.

Along with technological advances, studying the interactions between electromobility and biofuels could become a key research focus. A critical question is the timeline and the policy tools needed to effectively guide the transition, as well as how these technologies can work together during decarbonization. Hybrid and hybrid-flex technologies and infrastructure development are closely connected to building a sustainable transport system.

From a biofuels and sustainability perspective, additional research topics may include optimizing agricultural practices, improving energy and resource efficiency in production, and developing sustainability certification and control systems. Establishing targeted regulations and incentive mechanisms to promote responsible raw material sourcing and environmental compliance could also be an important area of study.

It is also important to consider that, although the growth of electric vehicles in road transport is significantly impacting liquid fuel demand, aviation and maritime transport also contribute substantially to greenhouse gas emissions. We briefly discussed SAFs (mainly in relation to the USA), but researching the environmental impact of SAF and the potential for GHG reduction in aviation and waterborne transport could be a valuable focus – especially since using SAF in aviation is now a goal of both the EU and the U.S.

Finally, research on social and economic impacts should also be expanded. These impacts include job creation, strengthening agricultural communities, and maintaining a balance between food and energy supplies. Achieving SDGs might require more societal involvement through increased awareness and changes in consumer habits.

6. Conclusions

Based on the study summary, it can be concluded that the long-term future of internal combustion engines raises serious questions, especially regarding environmental and sustainability issues. Meanwhile, the advantages of conventional technology – such as inexpensive fuel production, existing infrastructure, quick refueling, and reliable operation – face significant challenges primarily driven by their contribution to climate change and the limited availability of fossil resources. Environmental impacts, especially greenhouse gas emissions and urban air pollution, increasingly show that current technologies are unsustainable, making it necessary to transform the transport sector in accordance with sustainability standards.

However, the role of biofuels is complex. First-generation biofuels, which are made from food crops, raise ethical and sustainability concerns because they increase food insecurity and land-use changes, and they do not always remain CO₂-neutral throughout their life cycles. Second- and third-generation biofuels, especially those produced from algae and waste, offer a promising alternative because they combine sustainability and energy efficiency, but they also face technological and economic challenges, such as high production costs, limited infrastructure, and currently very low capacity.

Brazil's example demonstrates that high sugarcane yields, government support, technological progress, and a flex-fuel vehicle fleet work together to create a sustainable and economically competitive bioethanol industry. This industry helps achieve energy independence and meet climate policy goals. However, this model is hard to adopt in other countries because extreme climate and geographic conditions, along with the influence of government support systems, significantly impact

its success.

Global market trends indicate that biofuel production is growing rapidly, especially in the U.S., Brazil, and Asia. Meanwhile, in the EU, the share of traditional first-generation biofuels is declining due to stringent regulations and sustainability standards, while waste-based and advanced biofuels are gaining prominence. The future of the biofuel market is mainly shaped by technological advances, regulatory changes, fluctuations in the price and availability of energy resources, and the growing trend toward electromobility. The rise of electric vehicles will reduce the long-term need for liquid fuels, making biofuels more of a temporary solution. However, they will remain important in aviation, shipping, heavy cargo, and specialized applications. Developing a sustainable biofuels industry is therefore a strategic challenge that involves technological innovation, global markets, sustainability standards – including the circular economy model – and policy development.

In conclusion, current and future trends indicate that the role of internal combustion engines in transportation is gradually declining, while shifting to renewable energy sources and sustainable biofuels is unavoidable. Based on current projections, advanced and waste-based biofuels are gaining increasing global priority, but they cannot yet fully replace food-based biofuels, so the use of food-based biofuels cannot be entirely eliminated. The transition will be complex, involving multiple factors, and will vary across regions, but it will fundamentally support the goals of energy transition and climate protection. Biofuels will remain important during the transition period, but in the long term, electrification and electromobility are likely to dominate in decarbonizing transportation.

7. Recommendations for optimizing biofuel policy frameworks in Brazil, the United States, and the European Union

Building on the comparative assessment of Brazil's RenovaBio, the United States' Renewable Fuel Standard (RFS), and the European Union's RED III / ReFuelEU / Fit for 55 framework, it is evident that each system reflects distinct structural strengths and constraints (Table 4). Accordingly, policy recommendations must be context-specific, leveraging domestic resource endowments, institutional capacities, and technological trajectories, while addressing identified inefficiencies and sustainability risks.

For Brazil, the primary recommendation is to enhance the environmental robustness and long-term credibility of the RenovaBio framework without undermining its market-based efficiency. The CBIO system provides a strong foundation for cost-effective decarbonization – however, its effectiveness would benefit from increased regulatory stability and predictability in target setting, thereby strengthening investor confidence. In parallel, Brazil should integrate more explicit ILUC governance mechanisms into the RenovaBio certification system, particularly in relation to soybean-based biodiesel and agricultural expansion dynamics. Given the country's comparative advantage in sugarcane ethanol, policy efforts should prioritize high-efficiency, low-

carbon pathways, including second-generation (cellulosic) ethanol.

In the case of the United States, reform the RFS should focus on transitioning from a predominantly volume-based mandate toward a more carbon-intensity-sensitive framework. The U.S. should accelerate the deployment of advanced biofuels, including cellulosic fuels and SAF, by addressing persistent barriers such as technological risk, infrastructure gaps, and policy uncertainty. Reducing the structural dependence on corn ethanol would also mitigate concerns related to food-fuel competition and land use impacts. In terms of sustainability governance, strengthening the integration of ILUC considerations into regulatory decision-making would enhance the credibility of the system. Finally, given the rapid growth of EVs, U.S. biofuel policy should adopt a complementary positioning, focusing on sectors where electrification is less feasible, while avoiding inefficient overlap in light-duty transport.

For the European Union, the key recommendation is to balance its strong sustainability framework with greater flexibility and scalability in biofuel deployment. The EU has established a globally leading system in terms of GHG thresholds and ILUC governance – however, the increasing complexity of regulatory requirements may hinder investment and slow the scale-up of advanced biofuels. Given the EU's strategic prioritization of electrification, biofuels should be explicitly concentrated in hard-to-decarbonize sectors, particularly aviation and maritime transport, where alternatives remain limited. In this context, stronger and more predictable incentives for Sustainable Aviation Fuel (SAF) deployment are essential. Additionally, the EU should continue to support feedstock diversification, particularly waste- and residue-based pathways, while carefully managing supply constraints. From a global perspective, the EU could play a leading role in setting international sustainability standards, thereby influencing global biofuel markets and reducing the risk of carbon leakage.

In summary, while Brazil, the United States, and the European Union differ significantly in their policy design and strategic priorities, a common direction emerges: the need to integrate biofuel policies within a broader, multi-technology decarbonization framework. This includes aligning biofuels with electrification, strengthening sustainability safeguards, and promoting advanced fuel pathways. By combining market-based efficiency (Brazil), scalability (United States), and sustainability rigor (European Union), each region can enhance the effectiveness and long-term viability of its biofuel strategy.

CRedit authorship contribution statement

Csongor Máthé: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cintia Póka:** Writing – original draft, Resources, Investigation, Data curation. **Máté Zakar:** Writing – original draft, Visualization, Resources, Project administration, Methodology, Data curation, Conceptualization. **József Barnabás Tóth:** Writing – original draft, Resources, Investigation, Data curation. **Gergely Gyimóthy:** Writing – original draft, Resources, Investigation, Data curation. **Gábor Horváth:** Writing – original draft, Resources,

Table 4

Overview of Biofuel Policy Instruments in Brazil, the US, and the EU. Own editing. Source: [70,158,187,207,209].

Dimension	Brazil (RenovaBio)	United States (RFS)	European Union (RED III / ReFuelEU / Fit for 55)
Policy instruments	Market-based carbon credit system (CBIO)	Volume mandates (RVOs)	Blending mandates + GHG reduction targets + sub-targets (Advanced fuels, SAF)
Feedstock structure	Sugarcane ethanol dominant; Soybean biodiesel	Corn ethanol dominant; Soybean biodiesel; Limited advanced fuels	Diversified; Strong push toward Waste/Residue-based and Advanced biofuels
GHG thresholds	Lifecycle CI scoring, relative performance-based	Fixed thresholds (20–60% GHG savings)	Strict thresholds (up to 65–80% GHG savings)
EV competition	Limited: Biofuels dominant (flex-fuel vehicles)	Moderate: EVs growing but coexist with biofuels	Strong: Electrification is primary decarbonization pathway
ILUC governance	Limited explicit ILUC regulation	Weak ILUC integration	Strong ILUC framework, high-ILUC feedstocks restricted (e.g. palm oil)

Investigation, Data curation. **Tamás Tóth:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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