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OPINION

Biofuel technologies: Lessons learned and pathways to decarbonization

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Abstract

This Opinion highlights several successful cases of biofuel technologies recently described by the IEA Bioenergy Intertask Report on Lessons Learned. The report discussed the potential of biofuels to contribute to a significant market supply, thus replacing fossil fuels and mitigating global warming, and it underscores the challenges in expanding biofuel production and replicating successful models between countries and regions. Based on the lessons learned from conventional, established technologies, the authors analyzed policies, feedstocks, products, technologies, economics, environmental concerns, social aspects, scalability, and ease of implementation and replication in different countries or regions. There are blending mandates in place around the world to foster the use of biofuels. Dependence on the availability and price fluctuations of crop feedstocks may limit biofuel production in certain circumstances. Legal restrictions on using food crops as feedstocks present obstacles to scaling up production. Temporary constraints related to feedstock costs and availability, as evidenced by changes and postponements of biofuel blending mandates in various countries (particularly during the COVID-19 pandemic) also pose challenges. Technological hurdles exist for advanced biofuels that implicate premium pricing. Still, 2G ethanol from sugarcane meets very strict feedstock requirements with a carbon footprint so low that only electric vehicles charged in Norway could have life-cycle GHG emissions at the same level as a 2G ethanol-fueled combustion engine car. The authors evaluate whether and how much electrification could contribute to advance the decarbonization efforts in different countries. Drawing from these observations, the authors express their viewpoints to assist researchers and policymakers in the energy sector in formulating viable approaches to combat the climate crisis.

KEYWORDS
biodiesel, biorefinery, climate crisis, corn, ethanol, global warming, sugarcane

1 | COMPARING OPTIONS AVAILABLE TO DECARBONIZE TRANSPORT

The 2020s are a crucial decade for reaching the targets of the Paris Climate Agreement. The global GHG (greenhouse gas) budget for meeting the 1.5°C target is rapidly dwindling: it still amounted to 300 billion t of CO_2eq in 2021 according to the IPCC (Intergovernmental Panel on Climate Change), but every year, 42 ± 3 billion t of CO_2eq are released (IPCC, 2018). In fact, cumulative GHG emissions by 2020 were only 1% short of the cumulative emissions of the RCP 8.5 scenario, which is the worst-case climate change scenario adopted by the IPCC (Schwalm et al., 2020). Depending on the effectiveness of the measures implemented to reduce GHG emissions, the window of opportunity is just a few years. All the while, the effects of the climate crisis are becoming increasingly visible (Müller-Langer, 2023). After record-breaking temperatures in July 2023, the Secretary-General of the United Nations, António Guterres, declared that "the era of global boiling has arrived" (The Guardian, 2023).

One of the greatest action fronts against climate change is related to reducing the GHG emissions from the transport sector, which alone accounted for 16.2% of global emissions in 2016 (Ritchie et al., 2020). Recently, electrification of the transport sector has been praised as a solution to decarbonize the transport sector (Qiao et al., 2019). Despite electrification being very effective for some means of transport such as rail, it is not a silver bullet for the whole transport sector around the world. On the contrary, liquid biofuels such as ethanol and biodiesel are mature, scalable, and well-developed technologies with demonstrated low carbon footprint. Their use improves energy security and air quality in large cities, generates jobs and is allied to economic development. According to IRENA (IRENA, 2022), the share of biofuels in the transport sector is expected to grow nearly sixfold up to 2050, especially in developing countries. Currently, global biofuel production capacity sits at 4 PJ year^{-1}, with an additional planned or under-construction capacity of 2 PJ year^{-1} (Naumann et al., 2023). Total capacity is expected to reach 33–58 EJ year^{-1} by 2050 according to IEA (IEA, 2022).

Battery electric vehicles (BEV) have outstanding performance in terms of power and torque. However, to achieve a regular range, they need to carry heavy batteries. Battery manufacturing requires materials such as Li, Ni, and Co, of limited availability and whose processing demands energy and other materials, with a large production of GHG emissions (Peters et al., 2017). Moreover, BEVs demand electricity. Despite the recent and outstanding growth of renewable sources of electricity such as wind and solar power, the electricity mix of many countries cannot be considered as a clean energy source (Sokulski et al., 2022). Figure 1a presents the results of a literature survey (Bauer et al., 2021; Cho et al., 2023;

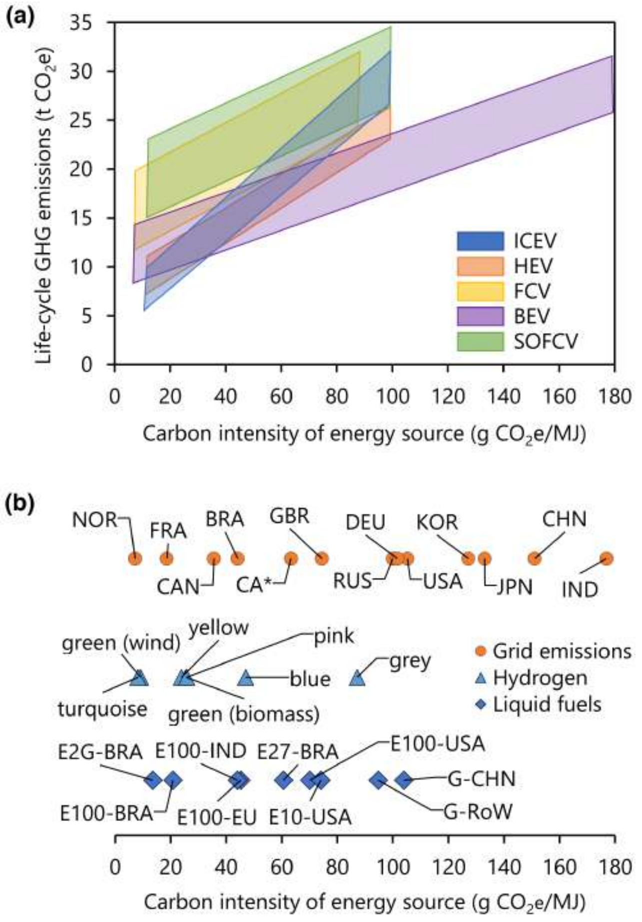

FIGURE 1 (a) Comparison of life-cycle GHG emissions of internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV), fuel cell vehicles (FCV), battery electric vehicles (BEV), and solid oxide fuel cell vehicles (SOFCV) for different carbon intensities of the energy source of the vehicle. (b) Comparison of the carbon intensity of energy sources used in these vehicles: electricity, liquid fuels, and hydrogen (Bauer et al., 2021; Cho et al., 2023; Del Pero et al., 2018; Diab et al., 2022; EPA, 2020; Faria et al., 2013; Giraldi et al., 2015; Howey et al., 2011; Marmiroli et al., 2018; Ou et al., 2009; Pereira et al., 2019; Tagliaferri et al., 2016; Velandia Vargas & Seabra, 2021). To compare the life-cycle GHG emissions of different vehicle technologies, first select an energy source in graph (b) and check its carbon intensity in the *x*-axis below; then, bring this value to the *x*-axis in graph (a) and check the corresponding life-cycle GHG emissions range in the *y*-axis for a suitable vehicle type. In grid emissions, countries are represented by their three-letter code according to ISO 3166, except for CA*, which corresponds to the state of California, USA. In hydrogen, colors indicate the different technologies for hydrogen production. In liquid fuels, E100, E27, and E10 represent different ethanol and gasoline blends in different countries or regions, and G represents pure gasoline in China (CHN) and the average in the rest of the world (RoW).

Del Pero et al., 2018; Diab et al., 2022; EPA, 2020; Faria et al., 2013; Giraldi et al., 2015; Howey et al., 2011; Marmiroli et al., 2018; Ou et al., 2009; Pereira et al., 2019; Tagliaferri et al., 2016; Velandia Vargas & Seabra, 2021) of the life-cycle GHG emissions of many types of vehicles (including battery electric and internal combustion engine), to which we varied the carbon intensity of the energy source according to their typical range across the globe, as shown in Figure 1b for electricity, liquid fuels, and hydrogen. Electricity may have clear benefits over gasoline despite its wide range of carbon intensity, which is very country dependent. However, blended gasoline and ethanol have the potential to deliver lower life-cycle GHG emissions, especially in countries whose electricity mix is not as clean as the Brazilian, Canadian, French, or Norwegian grids. For instance, an electric vehicle charged using electricity in Germany or the United States could produce about 40%–200% more GHG emissions over its lifetime than a sugarcane ethanol-powered vehicle using an internal combustion engine (Figure 1). This range increases to 80%–370% when considering the electricity from China.

Some authors argue that BEV reallocate emissions outside of urban areas (Ajanovic & Haas, 2016), but one cannot forget that the average lifetime of CO_2 is hundreds of years (Archer, 2005), which is enough for it to build up in the atmosphere and affect whole ecosystems globally. Finally, BEV are still expensive considering the average wage of consumers in developing countries (Rajper & Albrecht, 2020). Therefore, other immediate solutions need to be considered as well. Biofuels represent a cost-competitive option to reduce the GHG emissions from the transport sector over the next 10–20 years. Biofuels can be blended with regular fossil fuels and used in currently existing vehicles (Anderson, 2015). This avoids fleet replacement that could occur due to a ban on internal combustion engines, which has been proposed or established in several countries or regions (Senecal & Leach, 2019). Moreover, biofuels can use the currently existing refueling infrastructure. On the contrary, further development of recharging stations and reliable grid infrastructure across cities and highways is required for BEV, and the GHG emissions related to these are often neglected in life-cycle assessments. Biofuels are also a feasible solution to reduce GHG emissions of hard-to-electrify sectors, such as aviation and maritime transport, responsible for 22% of the GHG emissions of the transport sector (Ritchie et al., 2020).

The successful biofuel markets developed in Brazil, the United States, Indonesia, and other countries cannot be easily replicated elsewhere with the same environmental performance. However, maritime transport of biofuels across the globe has low impact on the life-cycle GHG emissions of biofuels (Castanheira et al., 2015), which means that they do not need to be locally sourced. Therefore, climate mitigation strategies should also focus on well-established biofuel technologies with stronger, proven impacts on GHG savings instead of solely focusing on electrification. Based on an IEA Bioenergy report produced by the authors (Cantarella et al., 2023), Sections 2–4 comment on the lessons learned from well-developed biofuel markets across the globe, with a discussion on the current state of new biofuel technologies in Section 5. Based on these lessons, the authors highlight some aspects to help researchers and policymakers of the energy sector in developing and implementing technically feasible solutions in the fight against the climate crisis as soon as possible, as discussed in Section 6.

2 | COMPARATIVE ANALYSIS OF BIOFUELS

Figure 2 shows a survey of biofuel blending mandates or market share in several countries (Biofuels Digest, 2023; Dina Bacovsky et al., 2022; Lieberz, 2021; U.S. Energy Information Administration, 2023). This survey contains data from various sources, and some numbers might be outdated. An evaluation of the political environment for their implementation is available in the literature as well (Souza et al., 2023; Trindade et al., 2019). Currently, more than 60 countries have blending mandates for biofuels and at least 17 countries have blending mandates specifically for advanced biofuels (REN21, 2021). In general, ethanol has a more widespread use because even low blending rates greatly increase the octane rating of gasoline, making it a formidable antiknocking agent in many gasoline formulations (Wang et al., 2017). Major markets for biodiesel are motivated mainly by the security of energy supply, but low blending mandates (<5%) are observed in many countries as well in an attempt to decrease GHG emissions from diesel engines. However, the use of these biofuels needs to be further increased to curb the rise of GHG emissions and limit global warming within tolerable limits.

Based on the assessment of the success stories of biofuels in many markets of the world, the authors devised a methodology to compare biofuel technologies and discuss their potential application and future developments in decarbonizing the transportation sector (Figure 3). This assessment primarily focused on well-established biofuels with high Technology Readiness Levels (TRL) with widespread use, especially corn and sugarcane ethanol and biodiesel. These biofuel technologies serve as benchmarks and success stories, setting the standards against which other potential biofuels (and other solutions to decarbonize transport) can be evaluated. However, it is important

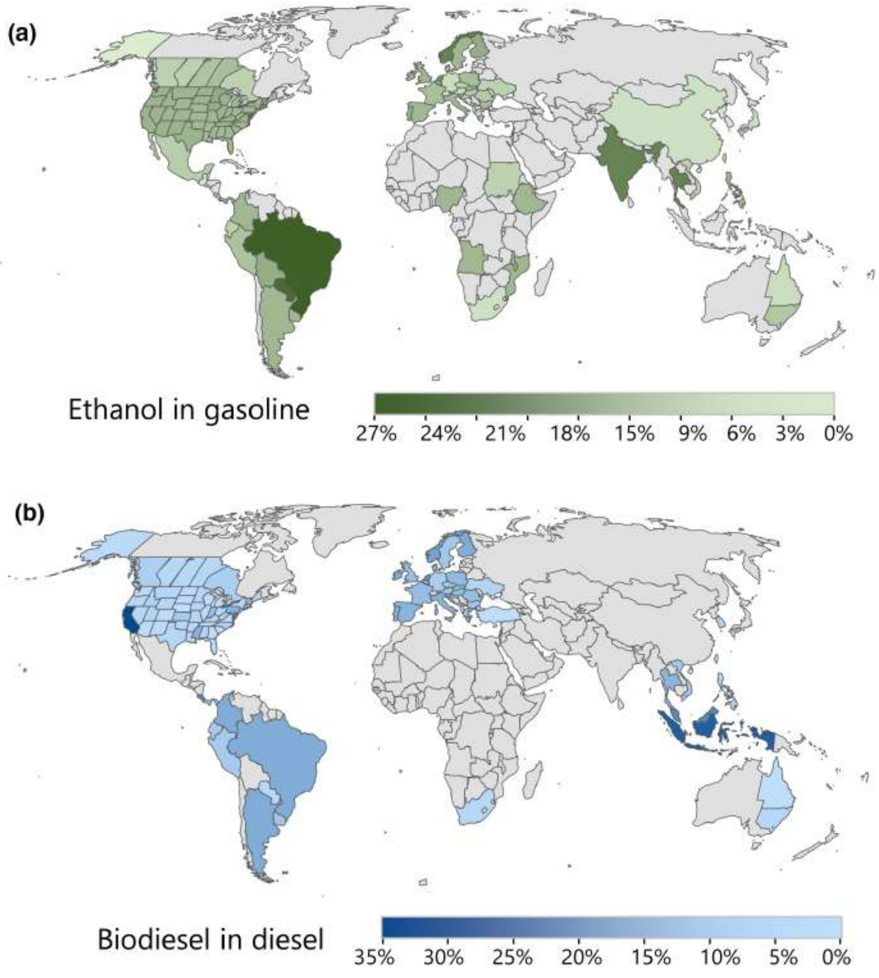

FIGURE 2 (a) Ethanol and (b) biodiesel blending mandates or market shares in many regions (countries, provinces, or states) across the world. Biodiesel includes FAME and HVO (Biofuels Digest, 2023; Dina Bacovsky et al., 2022; Lieberz, 2021; U.S. Energy Information Administration, 2023).

to acknowledge that future biofuel options will not simply replicate past successes. New standards, regulations, requirements, and legislation may significantly impact the characteristics of biofuels demanded by society. Additionally, the success of biofuels is often influenced by country or region-specific factors, such as land availability and feedstock resources, which determine the feasibility and cost-competitiveness of different bioenergy options. Moreover, incentives, particularly those related to innovation, play a crucial role in determining the future success of biofuels. Therefore, it is essential to consider examples of advanced biofuels such as 2G ethanol, HVO, BtL, and Bio-SNG.

According to Figure 3, in general, all the considered biofuels performed well in terms of meeting Sustainable Development Goals (SDGs), with an average score of 7 on a scale of 0 to 10. However, the success of biofuels relies on public policies and incentives, including tax incentives and blending mandates. The scores for these aspects were generally 8 or above. The production of by-products alongside biofuels was also deemed important for biomass valorization, resulting in high grades for most of the biofuels evaluated, except for Bio-SNG. The potential for implementation, replication, and scaling up biofuel production was rated high for all ethanol biofuels (both 1G and 2G), as well as for HVO and FAME biodiesel, which benefit from mature technologies and the availability of feedstock in several regions across the world. However, regional restrictions may arise due to concerns about raw materials competing with food production, whereas the approach should be focused on integrating the development of both food and fuel production to meet global challenges (Schulte et al., 2021). In 2010, only 1% of total arable land in the world was used for biofuel production, and only 5% would be needed in a scenario with a primary energy supply of 150 EJ year^{-1} from bioenergy by 2050 (Woods et al., 2015). Scale-up and replication scores were lower than 8 for Bio-SNG and BtL due to their high costs and ongoing technological development.

Environmental impact was an important criterion for grading biofuels. In general, most biofuels performed well, scoring between 8 and 10, as they have a high potential to reduce GHG emissions compared with fossil fuels. HVO and FAME biodiesel received a score of 7 due to their dependence on oil crops as feedstock, while corn ethanol produced in the US received a score of 4 because its GHG savings are relatively small compared with other biofuels evaluated in the study. The

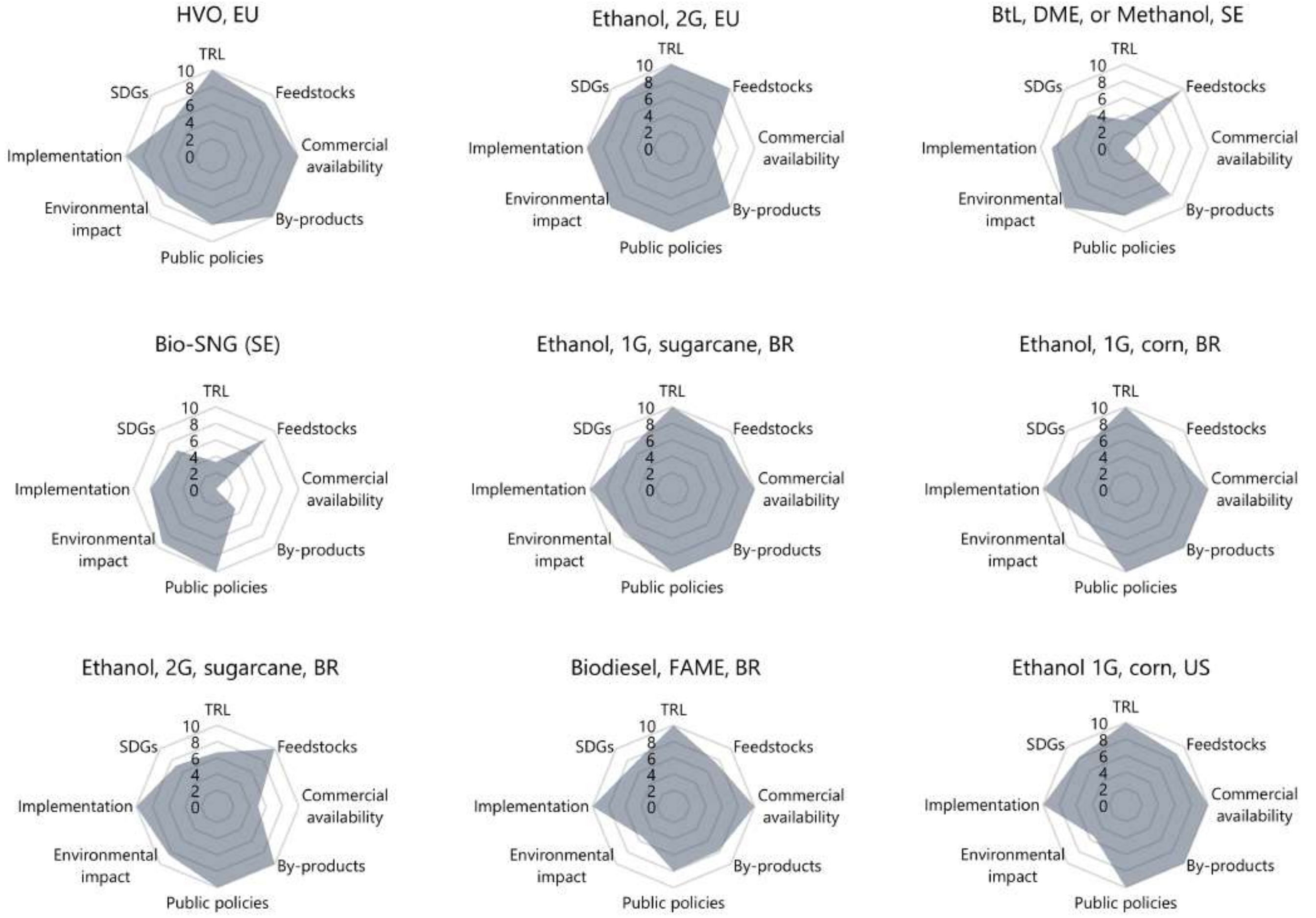

FIGURE 3 Spider graphs showing the scores of many biofuel technologies in different places across the world in the following categories: TRL (technology readiness level), feedstock, commercial availability, by-products, public policies, environmental impact, implementation, and compliance with SDGs (sustainable development goals). Full details of these classifications are available in the original IEA Bioenergy "Assessment of Successes and Lessons Learned for Biofuels Deployment" report (Cantarella et al., 2023).

availability of feedstock plays a crucial role in the success of biofuel production, and in this regard, all biofuels performed well, although feedstocks may vary in availability across regions.

The commercial availability of biofuels serves as a measure of their success stories thus far. Ethanol from sugarcane and corn is being produced and used in significant volumes in several countries, contributing substantially to biofuel targets worldwide. HVO and biodiesel (FAME) are also produced and used in sizable quantities in numerous countries. On the contrary, 2G ethanol is still emerging in Brazil and Europe, with the potential for additional viable plants in the future. In 2020, advanced biofuels (including HVO) were responsible for only 6.7% of the biofuel market (IEA, 2021). The feasibility of advanced biofuel projects depends on cost-effective technologies and the availability of large volumes of feedstock at low prices. Bio-SNG and BtL biofuels have partially successful stories but face cost limitations that have kept them at TRL 7. Nonetheless, given the favorable indicators in the grading system, these biofuels can progress to higher TRLs with appropriate incentives and technological advancements.

3 | THE ETHANOL INDUSTRY IN BRAZIL AND THE US

Ethanol, which serves as the primary biofuel in the global market, exhibits a concentrated production pattern with approximately 80% originating from just two countries: the USA and Brazil. Most of the consumed ethanol is presently obtained from well-established industries (technology readiness level, TRL: 9) utilizing corn (in the case of the USA) and sugarcane and corn (in the case of Brazil) as primary feedstocks. The United States contributes 57.0 million $m^3 year^{-1}$ of ethanol (94% from corn), while Brazil's production is 33.2 million $m^3 year^{-1}$ (83% from sugarcane and 17% from corn; AFDC, 2023; CONSECANA, 2023).

Figure 4 shows the evolution of the production of corn and sugarcane in the United States and Brazil, respectively, and the share of these crops used in the production of ethanol (AFDC, 2023; CONSECANA, 2023; EPE, 2021; FAO, 2023; UDOP, 2023). The rise in ethanol demand in the United States at the end of the 2000s, because of the implementation of the Renewable Fuel Standard, led to a substantial increase in corn price, which was soon reverted after relative blending targets were stabilized, contrary to beliefs of many critics on previous analyses reviewed in the literature (Condon et al., 2015). In the case of Brazil, sugarcane prices steadily decreased until the early 2000s because of increased crop yield and ethanol yield from sugarcane. Since then, sugarcane yields declined and stabilized because of the lack of investment caused by the economic crisis and indebtedness of the sugarcane sector. Climatic events such as extreme drought and frost can be blamed as well. The following yield stagnation in the 2010s can be attributed to changes in harvesting (mechanical harvest, which can damage the sugarcane ratoons), a problem that is being overcome. Nevertheless, industrial yield continued to improve over this period, and new developments in the industry are expected in the near term such as high-gravity fermentation (Puligundla et al., 2019).

In the case of corn ethanol, the industrial yield has been growing steadily since the beginning of the implementation of the Renewable Fuel Standard, while corn yield has been growing steadily since the 1950s because of the adoption of hybrid varieties and better agricultural practices (Kucharik & Ramankutty, 2005). As a consequence, the corn ethanol industry has increased the number of corn ethanol plants from 56 in 2000 to 199 in 2022, generating 78,802 direct jobs, 342,876 indirect jobs, and $34.8 billion in household income (RFA, 2023). In Brazil, the sugarcane ethanol market started to grow after energy security measures were put in place during the oil crisis in the 1970s; more recently, in 2020, the Brazilian government created the RenovaBio program, whose goal is to award decarbonization certificates to biofuel producers according to their carbon footprint, and these certificates are exchanged in the stock market (Ribeiro & da Cunha, 2022). This program has motivated producers to decrease their emissions even further because of economic benefits, and

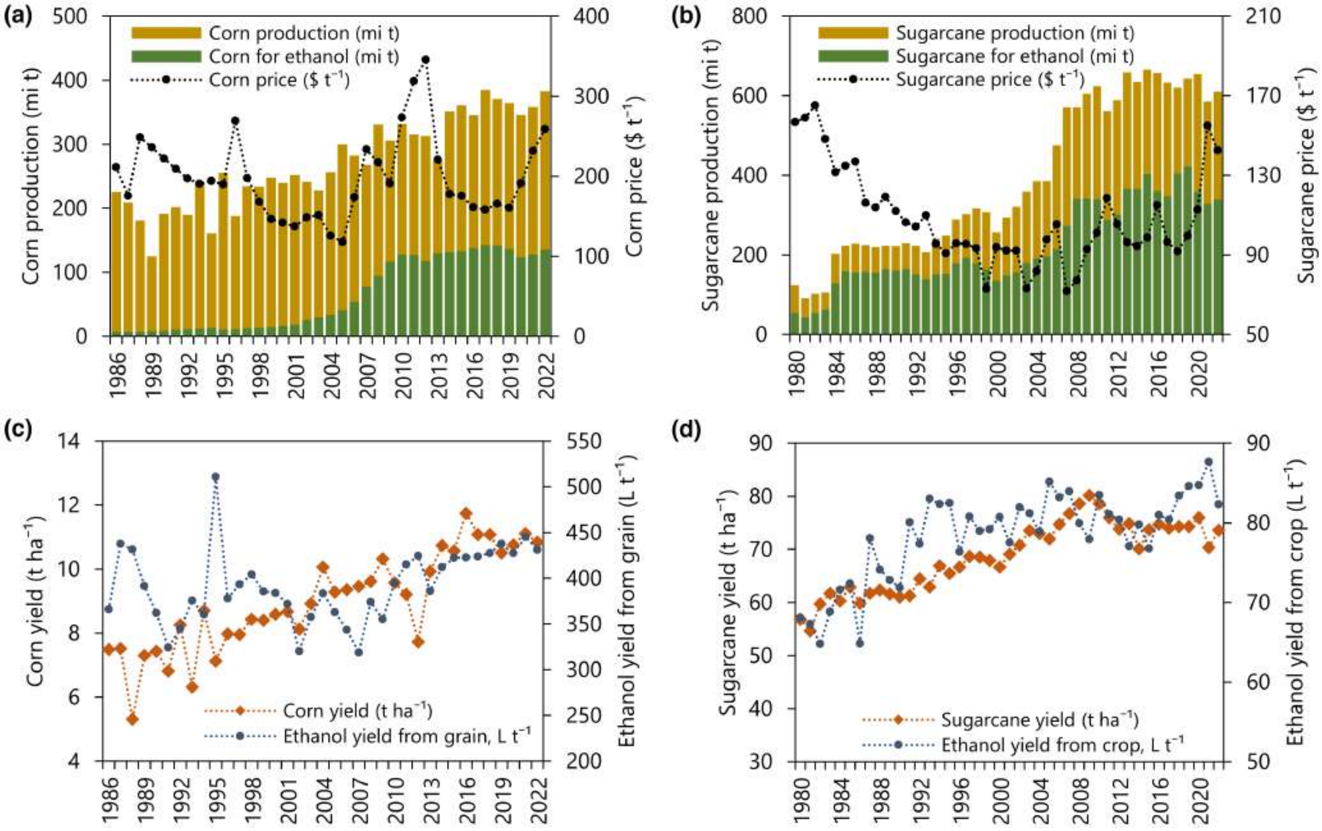

FIGURE 4 Historic data of production, usage for ethanol, and price of (a) corn in the United States and (b) sugarcane in Brazil (b), and agricultural and industrial yields for (c) corn/ethanol in the United States and (d) sugarcane/ethanol in Brazil (AFDC, 2023; CONSECANA, 2023; EPE, 2021; FAO, 2023; UDOP, 2023).

it is expected to avoid the emissions of 620 Tg CO_2eq by 2030 (EPE, 2021). These examples demonstrate the power of local government action in the development of biofuel markets.

Sugarcane produced in Brazil has the highest yield of ethanol per hectare (6.0 $m^3 ha^{-1}$, against 4.4 $m^3 ha^{-1}$ for corn in the United States, average of last 10 years, Figure 4). However, this value can be improved by using different sugarcane varieties and its residues such as bagasse (10–12 $t ha^{-1}$, dry weight) and straw (10–12 $t ha^{-1}$, dry weight, leaving about 7 $t ha^{-1}$ in the field for soil conditioning) in second generation ethanol processes. Besides, sugarcane biorefineries use bagasse as boiler fuel and produce surplus electricity. For instance, in 2022, sugarcane biorefineries in Brazil produced 24 TWh—more than coal, oil, and nuclear sources combined in the country (ONS, 2023). On the contrary, corn ethanol also has coproducts, such as corn oil (18 $L t^{-1}$ of corn) and dried distillers grains with solubles (DDGS, ~310 $kg t^{-1}$ of corn). Food grade CO_2 from fermentation also has its applications, and it further decreases the global warming potential of ethanol—30% of ethanol plants in the US capture CO_2 from fermentation (Scully et al., 2021). Moreover, industrial performance has contributed to a steady decline of 23% in the global warming potential of American corn ethanol from 2005 to 2019 (Lee et al., 2021).

Corn ethanol started to develop in Brazil in 2017, and in 2022, it already contributed to 17% of the total ethanol production in the country (CONSECANA, 2023). An interesting aspect of this development is that many corn ethanol plants in Brazil are being integrated into existing sugarcane mills. This integration requires less investment because it takes advantage of facilities that otherwise would be idle during the sugarcane off-season (which lasts about 45% of the year; Sumikawa & Medeiros de Lima, 2021). Besides the economic benefit and the feedstock diversification aspect (Gonçalves et al., 2023), this integration decreases the carbon footprint of corn ethanol because the surplus renewable energy from the sugarcane process can be used instead of natural gas as boiler fuel, which is used in the corn ethanol process in the United States. In the case of corn ethanol in the United States, the production process accounts for about 49% of total GHG emissions of ethanol, majorly because of the use of a fossil energy source (Pereira et al., 2019). On the contrary, it is estimated that corn ethanol in Brazil produced from double-cropped corn combined with soybean has a carbon footprint of 26 $g CO_2 MJ^{-1}$ (Moreira et al., 2020). Besides using renewable biomass as boiler fuel, this production model reduces the requirement of nitrogen fertilizer for corn because of the presence of nitrogen-fixing bacteria associated with soybean crops.

4 | THE BIODIESEL INDUSTRY IN ARGENTINA, BRAZIL, INDONESIA, AND THE US

The main biodiesel producers are Indonesia, Brazil, and the United States, as seen in Figure 5a. Biodiesel production has increased by 95% from 2011 to 2021, and its share in total biofuel production has increased from 31% to 42% (BP, 2022). Indonesia is the major biodiesel-producing country thanks to the high yield of oil palm, a major crop in that country. Indonesia is pushing for the increased use of biodiesel because fossil oil production currently supplies about half of the consumption (Ichsan et al., 2022), making the country very dependent on the international oil market and compromising its energy security. The local government instated regulations to support the local biodiesel industry via a blending mandate, which is set at 35% as of February 2023 (Rahmanulloh, 2023). Of course, such a high biofuel blend might create criticism over the possible damage to diesel engines. Therefore, Indonesia's government has been carrying out tests on B40 blends

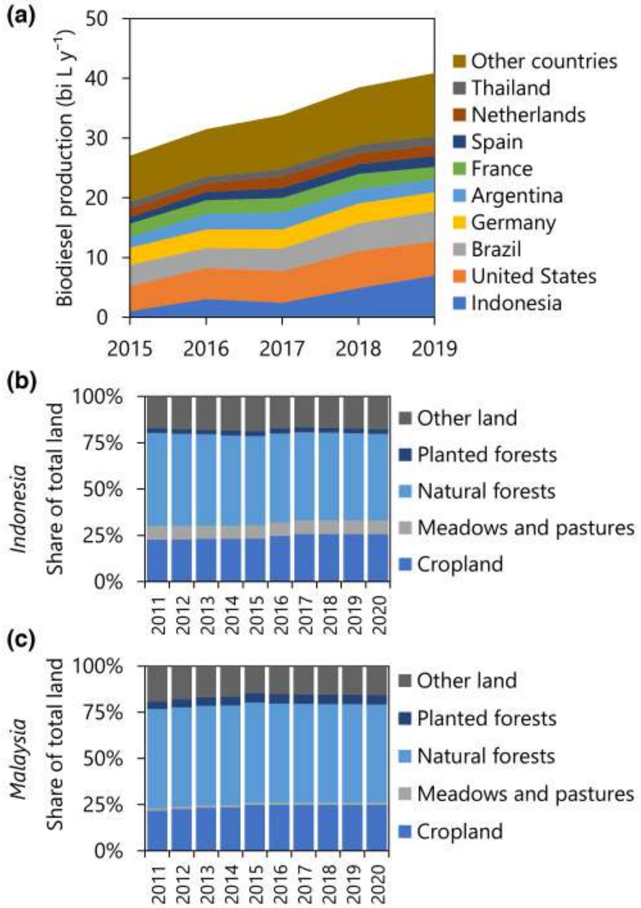

FIGURE 5 (a) Biodiesel production across the world and share of land according to different uses in (b) Indonesia and (c) Malaysia.

containing either 30% FAME (fatty acid methyl ester) and 10% DPME (distilled palm methyl ester) or 30% FAME and 10% HVO (hydrotreated vegetable oil—made from palm oil; Reuters, 2022). The state oil company, Pertamina, is set to produce 1.15 million m^3 of HVO by 2024 to accommodate the increase in blending mandate.

The establishment of new palm plantations has been recognized as one of the primary drivers of peatland degradation in Indonesia and Malaysia (Tonks et al., 2017). Indonesia has lost 8.5% of its forest cover from 2011 to 2021, and 3.8% since the establishment of the country's aggressive biodiesel policy in 2015 (FAO, 2023). In the case of Malaysia, the natural forest cover has decreased by 1.4% from 2011 to 2021. Criticism over environmental degradation in these countries by the international community has driven the establishment of peatland restoration projects that have been contributing to recovering biodiversity, fire regulation, and carbon sink capacity of peatlands (Tonks et al., 2017), demonstrating the potential of the biofuel industry to improve its practices. Planted forest area has increased by 12% in Indonesia and 31% in Malaysia from 2011 to 2021 (FAO, 2023), thus showing that the final use of the land area in these countries remains mostly constant as seen in Figure 3. However, these initiatives failed in recovering the water retention capacity of degraded peatlands (Tonks et al., 2017). Therefore, additional measures are needed to lessen the land-use change impacts caused by the expansion of the biofuel industry in these areas and improve the sustainability of oil palm biodiesel.

In the United States, Brazil, and Argentina, soybeans are the primary raw material used for biodiesel production. In Brazil, the introduction of biodiesel blending began at a 2% level in 2008 and gradually increased to 12% in 2020. Soybean accounted for 66% of the feedstock used for Brazilian biodiesel production in 2022, while noncrop feedstocks such as tallow, lard, schmaltz, and used cooking oil contributed 7.9%, 3.0%, 1.2%, and 2.3%, respectively (ANP, 2023). Around 16% of the Brazilian soybean is used for biodiesel production, and the majority is exported as grain (EPE, 2021). Biodiesel in Brazil also benefits from climate conditions that allow double cropping, making soybean very suitable for crop rotation with corn (Moreira et al., 2020), as explained in the previous section.

Biodiesel currently represents approximately 11% of diesel consumption in Brazil, with 70% of the fossil diesel being locally produced and 19% imported (EPE, 2021). The implementation of blending mandates has played a crucial role in driving the expansion of biodiesel production in Brazil and ensuring the security of energy supply, as observed in Indonesia. Currently, the biodiesel capacity in Brazil stands at 10.4 million m^3, exceeding the current demand of 6.4 million m^3. Therefore, there is capacity for further production and utilization in Brazil. Argentina also holds a prominent position in biodiesel production within Latin America (Canabarro et al., 2023), producing approximately 2.2 million m^3 of biodiesel from soybean in 2022. Around 48% of this biodiesel was exported to Europe. By 2021, Argentina was expected to have around 33 operational biodiesel plants with a combined capacity of 4.4 million m^3 (Ciani, 2023). These developments have been encouraged by recent legislation enacted by the Argentinean government. A recent study demonstrated the potential to substantially increase biofuel production in Argentina, Brazil, Colombia, and Guatemala using very little of their existing pastureland (~5%; Souza et al., 2023).

It is important to bear in mind that blending mandates guide markets, foster investments and should be preserved as public policies to avoid untimely government interventions. For example, while the ethanol content in Brazilian gasoline can vary between 18.0% and 27.5% depending on price and availability of ethanol, the biodiesel content evolved progressively, increasing by 1 p.p. each year, starting at 10% in 2018, and was aimed to reach 15% in 2023. However, during the surge in vegetable oil prices in 2021 because of the COVID-19 pandemic, the Brazilian government decided to reduce the mandate from 13% to 10%. The gradual increase program was resumed only in 2023. Similar adjustments or postponements of blending mandates have been observed in other countries, and it is noteworthy that when the oil price rose sharply and unpredictably, the government has not considered accelerating the biodiesel blending program.

5 | BIOFUEL TECHNOLOGIES THAT REQUIRE FURTHER INVESTMENT

5.1 | Hydrotreated vegetable oil (HVO) in Europe and Indonesia

HVO consists of paraffinic, straight chain hydrocarbons of high cetane number that are produced via hydroprocessing of vegetable oil, thus being an alternative route to esterification to produce diesel engine-compatible biofuels. The chemical composition of HVO is similar to that of fossil diesel, which allows increased blending rates and longer storage time when compared to conventional biodiesel (FAME; IEA, 2019). These factors contributed to the increased interest of countries using high biodiesel blending mandates (such as Indonesia), and projects are being developed in other countries as well. The hydroprocessing of vegetable oil is similar to the hydroprocessing used in oil refineries to reduce sulfur content in diesel, which motivates the retrofit of existing oil refineries. For instance, the process has been successfully implemented in the La Mède refinery in

France, operated by TotalEnergies with a production capacity of 500 kt year^{-1} (Chapus, 2017). The biorefinery's flexibility in terms of feedstock and the ability to process resources from different regions contribute to its success.

Additionally, HVO plants generate by-products such as naphtha and propane during the hydrogenation process, which are more valuable than glycerol. HVO holds the potential for replication and global implementation. Shell has announced the construction of a facility in the Netherlands with an annual production capacity of 820 kt year^{-1} to produce HVO and sustainable aviation fuel (SAF; Shell Global, 2021). Worldwide HVO production is expected to double from 2018 to 2024, especially because of new projects in Europe and the US (IEA, 2019). Other large HVO projects have been announced in other countries as well, such as the Omega Green Project, in Paraguay, with 900 kt year^{-1} capacity (ECB Group, 2022) and the expansion of the Neste refinery in Singapore, recently expanded to 2600 kt year^{-1} (Neste, 2023).

5.2 | Biomass gasification and pyrolysis in Europe

Biomass can undergo thermochemical processing. These routes include the production of syngas, pyrolysis oil, methanol, and other liquid biofuels through Fischer–Tropsch synthesis and biomass-to-liquid (BtL) routes. Residual biomass is a valuable resource without direct competition with other land uses. Sourcing the biomass feedstock may pose challenges, but the products have a low environmental impact. For instance, diesel made from switchgrass and short rotation plantations are estimated to result in land-use GHG emissions of −12 to −29 $gCO_2eq\,MJ^{-1}$, respectively (Achinas et al., 2019). In another example, the BioDME project in Sweden uses black liquor (a residue of the Kraft pulping process) to produce methanol and dimethyl ether (DME) via gasification. Between 2011 and 2013, the project produced around 390 t of DME and field tests were conducted on trucks covering over 800,000 km (Salomonsson, 2013). In another example, the bioliq® process developed by the Karlsruhe Institute of Technology involves a decentralized step in the production of pyrolysis oil from biomass and a central step involving gasification and fuel synthesis (Dahmen et al., 2017). Additionally, the SynBioPTx concept explores the advantages and synergies of integrating biomass and power-based processes, aiming to increase carbon efficiency and potentially reduce production costs (Müller-Langer et al., 2019; Pregger et al., 2019). Cost remains a significant limitation for BtX processes, with capital expenses heavily contributing to the production cost; thus, economies of scale are needed to decrease this contribution.

Synthetic natural gas from biomass, also called Bio-SNG, is a renewable form of synthetic natural gas produced from wood residues via gasification. The GoBiGas project, operated by Göteborg Energi in Sweden, had a production capacity of 20 MW (ARTFuels, 2020). This biofuel can be employed in both light- and heavy-duty vehicles, while also generating district heating as a valuable by-product. The project received support from the Swedish Energy Agency, amounting to approximately €20 million, along with tax exemptions for the sale of Bio-SNG. In comparison with fossil fuels, the biofuel produced through this process can reduce GHG emissions by around 80% (ARTFuels, 2020). The gasification method used in this project makes it feasible and applicable on a global scale, as it relies on the utilization of residual biomass. The facility was initially planned to reach a maximum capacity of 100 MW (Alamia et al., 2017).

5.3 | 2G ethanol in Europe and Brazil

Despite the many hurdles faced in the past, 2G ethanol seems to have become a reality now. Raízen has been operating a plant with a capacity of 120,000 m^3 year^{-1} using proprietary technology developed over the past 15 years (Chandel et al., 2021). Clariant's Sunliquid technology has demonstrated production of 62,000 m^3 of ethanol in Germany in a precommercial facility, and it has been licensed in 2022 for a 50 kt year^{-1} ethanol facility in Romania using wheat straw (Raj et al., 2022). ENI has resumed the commissioning of a 25 kt year^{-1} of ethanol plant in Italy, which has been operational since 2022 (Singh et al., 2022). These 2G ethanol plants are self-sufficient because they use lignocellulosic residues of hydrolysis.

Nevertheless, the capacities of these ethanol plants are far from those of conventional ethanol plants and have limitations in supplying the market demand for fuels, even considering modest blending targets. Raízen is building other three 2G ethanol plants in Brazil at a capacity of 82,000 m^3 year^{-1} each, but it seeks markets that pay premium prices because of process costs. Strict regulations such as Renewable Energy Directive II of the European Commission limit the use of biofuel feedstocks to those that do not fit into the food/feed chain (Wu & Pfenninger, 2023), thus increasing the opportunity of further developing 2G (second generation) ethanol processes. Indeed, 2G ethanol from sugarcane meets very strict feedstock requirements of the Renewable Energy Directive II and it has a very small carbon footprint (13.6 $gCO_2eq\,MJ^{-1}$; Raízen, 2021), fit for these premium prices. Considering this low carbon footprint, only BEV charged in Norway (whose electricity comes majorly from hydroelectric power plants) could have life-cycle GHG emissions at the same level as a 2G ethanol-fueled internal combustion engine (Figure 1).

5.4 | Sustainable aviation fuel (SAF) in Europe and the US

Pressure over the aviation industry, responsible for 1.9% of global GHG emissions (Ritchie et al., 2020), has been motivating many advances in SAF production. SAF can be produced via hydroprocessing of vegetable oils and animal fats (co-product in HVO production), Fischer–Tropsch synthesis, or the alcohol-to-jet process (dehydration, oligomerization, and hydrogenation of ethanol; Klein et al., 2018). Gevo, Fulcrum, and Neste are important players in the development of this market. American and European airline companies are committing to buy SAF in long-term (3–10 years) contracts from these producers (Ng et al., 2021). The Gevo process is based on the alcohol-to-jet process in South Dakota, US, using American corn as the feedstock. Fulcrum uses Fischer–Tropsch synthesis based on municipal solid waste, in a facility in Nevada, US (Brandt et al., 2022). In general, the hydroprocessing route has the lowest production cost, lowest GHG emissions, and best technical feasibility (Klein et al., 2018; Ng et al., 2021), although it can suffer from feedstock competition with other biofuel markets (Dodd & Yengin, 2021). The Neste plant in Singapore is currently the largest vegetable oil hydroprocessing facility in the world, producing HVO and SAF (Neste, 2023). The alcohol-to-jet process can be integrated into sugarcane ethanol production as well, with significant synergies. However, assuming 2011 technology, oil barrel price of $70, and hydrogen produced via water electrolysis using renewable electricity, SAF from sugarcane ethanol is 58% costlier than conventional jet fuel (Klein et al., 2018). Therefore, additional investments are required to improve the economics of this route.

6 | OUTLOOK FOR BIOFUEL TECHNOLOGIES AND MARKETS

The quest for biofuels with robust sustainability indicators has stimulated research into new biofuels and alternative production methods. These endeavors prioritize biomass residues, feedstocks that do not compete with food production or plants that thrive in nonagricultural lands (Schmer et al., 2014). However, these novel biofuels or production routes did not evolve through a learning curve as the conventional biofuels did (Goldemberg et al., 2004). Therefore, their success demands increased research efforts, innovation, incentives, and public policies to navigate the challenging path toward economic viability. Comparing these advanced biofuels with conventional biofuels is a crucial step in their journey toward commercial viability. Valuable lessons learned from traditional biofuels can identify gaps and provide insights that may contribute to their success (Duan et al., 2012).

Conventional biofuels like ethanol and biodiesel, produced and used in various countries, are currently the leading alternatives to fossil fuels. Their yields, costs, and environmental performance have improved, thanks to long-term research, blending mandates, and supportive policies that increased investment and resulted in better agricultural and industrial performance. The economic crisis resulting from the COVID-19 pandemic and the Russo-Ukrainian war has impacted biofuel blending mandates and usage worldwide because of supply chain constraints, which affected oil prices as well. The pandemic has negatively affected production, trade, and investment in both conventional and advanced biofuels. Urgent action is needed to recover biofuel production and use.

Advanced biofuel routes such as 2G ethanol, BtL, Bio-SNG, and HVO demonstrate promising environmental impact, significant contribution to the sustainable development goals, and feedstock diversity, making them viable for replication in different regions. However, addressing technical hurdles and cost limitations is crucial and requires dedicated research and time. And despite the urgent need for progress because of the climate crisis, insufficient effort is being considered to foster these technologies. And the clock is ticking. Meanwhile, mature conventional biofuel technologies are being overlooked despite their potentially proven GHG savings compared with other better-marketed options to decarbonize the transportation sector.

Most biofuels available today, such as 1G ethanol, biodiesel, and HVO, are derived from crops, including food crops, and face restrictions in some regions. This poses a dilemma as successful biofuel production technologies encounter barriers to global implementation. Nonetheless, these biofuels have provided valuable insights and set benchmarks for new biofuel technologies with lower TRL. At this point, other biofuels produced exclusively from crop residues and nonfood crops seem not to be economically produced on a scale large enough to replace the current volume of conventional biofuels. Given the urgency of the climate challenge, pertinent questions include: Should we place strong restrictions on feedstock for biofuels when we still do not have viable biofuel technologies that use only crop residues as feedstocks? Can we sustainably use land to produce food and biofuel feedstock, at least in some countries or regions? An honest discussion is needed if biofuels are to be included in the menu of renewable energies to reduce global GHG emissions, as expressively suggested by the IEA and IRENA (IEA, 2021; IRENA, 2022).

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CONFLICT OF INTEREST STATEMENT

We report that G.M.S. is a subject editor at GCB Bioenergy at the time this paper was accepted for publication. However, this does not affect the views expressed in the paper by the authors.

DATA AVAILABILITY STATEMENT

The data that support the discussion presented in this work are available in the report "Assessment of Successes and Lessons Learned for Biofuels Deployment", published by IEA Bioenergy TCP, and listed in the References section.

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