

Article

The U.S. Biodiesel Outlook: A Pathway Toward Sustainability

Deepayan Debnath *, Jarrett Whistance and Wyatt Thompson

Food and Agricultural Policy and Research Institute, University of Missouri, 200 Mumford Hall, Columbia, MO 65211, USA

* Correspondence: debnathd@missouri.edu

Abstract: Policies to support renewable fuels are associated with economic and environmental sustainability in the United States and relate to the United Nations' sustainable development goals. Consequently, these fuels have been subject to scientific scrutiny and public debate; however, new developments in biomass-based diesel can overturn past understandings and create new trends and questions. An applied economic model of these fuels, their feedstocks, and related markets is used to project volumes and associated GHG emissions into the medium-term future. Results suggest a growing use of renewable diesel that directly displaces diesel and some recovery in biodiesel use, a near-substitute fuel. Yellow grease (used cooking oil)-based feedstock usage rises, while soybean and similar oil use remain stable. The expansion of renewable diesel made from yellow grease is associated with lower GHG emissions given the regulatory settings, but these projections also raise questions about the implications for environmental and economic sustainability.

Keywords: climate change; food security; sustainability; renewable fuels; GHG emissions; renewable diesel; biodiesel

1. Introduction

The United Nations defines 'Sustainability' as meeting our current needs without imperiling our future generations' requirements [1]. In the U.S., the Environmental Protection Agency (EPA) defines sustainability as creating and maintaining co-existing conditions where both humans and nature can live [2]. Sustainability might more generally refer to the integration of environmental, social equity, and economic development, which creates a resilient community that would sustain generation after generation. In this context, the United Nations Sustainable Development Goal (SDG) 7—clean energy—encourages the use of biofuels instead of fossil fuels [3].

A key aspect of biofuels that makes them relevant to sustainability is their potential to reduce greenhouse gas (GHG) emissions relative to the fossil fuels that they can displace. In that regard, emission reductions from biofuels can occur in any industry where fossil fuels are used, including the electrical energy sector, though our focus here is on the use of biofuels in the transportation industry. Many previous studies focus on the impact of ethanol and biomass-based diesel on lowering GHG emissions [4–7]. However, the potential of biomass-based diesel to contribute toward sustainability goals needs to be updated because of the newly evolved critical renewable fuels and feedstocks. In this study, we focus on the past, current, and future development of the biomass-based diesel sector in the United States and on the international market through trade. We further discuss the related feedstock markets, including vegetable oil and used cooking oil, and their impact on GHG emissions.

The focus here is on biomass-based biodiesel, which is typically derived from renewable lipid-based feedstocks, including used cooking oil (UCO) [8], palm oil [9], soybean



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oil [10], microalgae [11], and rapeseed oil [12]. This fuel has been found to be an environmentally friendly renewable energy source [13,14], so this renewable fuel is relevant to societal goals that seek sustainable sources of energy. UCO-based biomass-based diesel production is a key focus of policymakers who might judge that fuel from this feedstock could help to address climate change-related global challenges. This feedstock-fuel pairing might not compete directly with food crops while substantially reducing greenhouse gas emissions compared to fossil fuels [15], at the same time promoting sustainable economic growth [16]. Sustainable biomass-based diesel production is intended to lower the negative environmental impacts of moving people and goods or the transportation sector, making it relevant as a low-carbon alternative renewable energy source compared to conventional fossil fuels [17]. However, the impact of biomass-based diesel on several key aspects, such as decreased GHG emissions [18], energy sources diversification [19], regional economic development [19], waste management [20], forest protection [20], energy independence [21], and social sustainability [22] remain topics of study. In short, UCO-based biomass-based energy is a newly developed critical product whose contributions to societal goals are under study.

The production and use of biomass-based diesel from UCO have surged in the United States, providing an excellent case study about this fuel's causes, effects, and relevance to the societal energy mix and sustainability goals. The production and use of biofuels in the United States increased significantly, although the U.S. transportation sector still heavily relies on fossil fuels [23]. The Renewable Fuel Standard (RFS) sets the biofuel use mandates in the United States. The RFS establishes an overall use target that can be met by using corn starch-based ethanol. All newly qualifying renewable fuels must reduce GHG emissions by 20%. The RFS biomass-based biodiesel mandate requires that qualifying renewable fuels reduce GHG emissions by 50% [24]. Renewable biomass-based diesel fuels qualify as either of two types of products: (1) fatty acid methyl ester (FAME) biodiesel, which is produced through the esterification process, and (2) renewable diesel (RD), which is produced through a hydrotreatment process to create molecules similar to those produced through typical petroleum refining. Generally, FAME biodiesel is only mixed with petroleum diesel at a blending rate of up to 20%. Thus, biodiesel is an imperfect substitute for petroleum-based diesel, with consequently an upper limit on the scope for this fuel to contribute to sustainability goals.

Renewable Diesel has an identical chemical composition to petroleum-based diesel; RD is a "drop-in" fuel that could, in principle, displace any amount of petroleum-based diesel. The production of renewable diesel in the U.S. has been increasing substantially. More recently, market analysts have discussed the potential for sustainable aviation fuel to become an essential third type of renewable fuel in the future; however, we do not explore this possibility at this time. Past scientific assessments focusing on biodiesel might tend to miss these newly important fuels and consequently lose relevance when assessing current policy decisions or market outcomes as compared to sustainability goals.

Feedstock shares have also shown dramatic new patterns. Historically, crop-based feedstocks were used to produce biofuels; for example, corn for ethanol and vegetable oil for biodiesel. However, in the recent past, there has been a shift in feedstock use for biomass-based diesel from vegetable oil to used cooking oil, tallow, and distiller corn oil (DCO) due to the lower carbon intensity (CI) of renewable fuels made from these feedstocks relative to other inputs [25]. Based on lifecycle GHG emissions analysis, used cooking oil has the lowest carbon intensity at 20.70 gCO₂e/MJ, while soy oil has the highest CI at 58.00 gCO₂e/MJ. Conventionally, soy oil-based FAME biodiesel dominates U.S. biomass-based diesel production. More recently, renewable diesel production has increased threefold

from 2018 to 2022 [23]. Once again, studies focusing on biodiesel from soybean oil might lose relevance as new feedstocks and new fuels have started dominating the U.S. market.

The focus of this study is to estimate the shift in biomass-based biodiesel toward renewable diesel and relevant feedstock usage. We project the future production of biomass-based biodiesel and feedstocks, differentiating fuels and also among the various vegetable oils and waste products used as feedstocks. Furthermore, we estimate the future GHG emissions, taking into account the volumes of biomass-based diesel and the increasing share made from lower CI feedstocks. The future evolution of these fuels and feedstocks is relevant to markets, agricultural and climate policy, and GHG emissions. The potential for biodiesel to replace some petroleum products and renewable diesel to more fully displace such fuels opens up the potential for a vastly greater share of renewable fuels in the future as compared to anything possible in the past. The ongoing transition of feedstocks can have broader implications for food security and food policy, as well. Feedstocks made directly from vegetable oils that are widely applied in existing human uses, such as soybean and palm oil, might have hit a plateau in the U.S. At the same time, the used or waste oil share has risen dramatically in the U.S., and these feedstocks are not so clearly connected to food uses, causing some to speculate that biomass-based diesel made from them have additional value in terms of both climate and food effects in addition to their capacity as a liquid fuel. The forward-looking analysis used in this study moves from these current trends to explore the future evolution of key volumes, highlighting the scope for growth in biomass-based diesel made from used oils and other renewable sources and their interactions with market prices and GHG emissions.

2. Methodology

2.1. Model Structure

For this outlook, we employ a structural, multi-market, multi-region partial equilibrium model of supplies, demands, and prices for U.S. and international agriculture and biofuel markets. The model is rooted in the economic theory that governs producer and consumer behavior in commodity markets, which leads to market equilibrium prices under a set of key assumptions for the projection period, such as normal weather patterns and current government policies. In other words, we are not projecting based only on historical data trends, nor are we assuming new or different weather patterns and government policies. This approach has been used extensively to produce forward-looking outlooks for those key commodity markets [26] and to analyze policies, climate-related effects, and other market shocks (e.g., [27–31]). More broadly, it fits within the outlook literature alongside a host of other structural equilibrium models of markets that are widely used in similar analyses, such as GTAP, FASOM, Aglink–Cosimo, and AgMIP contributors.

Detailed descriptions of the larger modeling system have been published elsewhere (e.g., [32,33]); however, we focus here on the biofuel portion of the model as detailed in [34]. While earlier versions of this model have been used in other forward-looking analyses to examine the effects of changes to current biofuel policies [27,28,30], the starting point of the model for this outlook is the current version as of August 2024 [26,35].

In the model, biomass-based diesel production is broken down into the sub-components of fatty acid methyl ester (FAME) biodiesel, renewable diesel (RD), and sustainable aviation fuel (SAF). Production of each sub-category is determined by the net returns over input costs incurred by competitive biofuel producers in that market. Net returns are calculated for each of four primary feedstocks: virgin soybean oil, virgin canola or rapeseed oil, distillers corn oil, and used cooking oil. Feedstock demand is allocated as a share of total biomass-based diesel production, and each share is determined by the relative prices of those feedstocks. The feedstock demands are then transmitted to other

market modules for broad consistency among renewable fuel and commodity markets. In particular, the feedstock use is part of the total demand in the vegetable oil complex, affecting those market-clearing prices and going on to affect the demands, supplies, and prices of annual crops, livestock products, and other agricultural commodities.

The demand for biomass-based diesel is estimated as a function of its own price as well as the demand for diesel-type fuels in general. Diesel-type fuel demand, in addition to own prices, depends on factors such as population and consumer income. Trend variables for both biomass-based diesel and petroleum diesel help capture other market dynamics, such as aging populations that drive less or shift toward more fuel-efficient vehicles.

The effects of policies are incorporated into the determinations of supply and demand, as well. The Renewable Fuel Standard (RFS) volume obligations are assumed to grow modestly over the projection period as there is no official “sunset” for the law, and it is assumed that the U.S. Environmental Protection Agency (EPA) will continue to set standards that encourage further adoption of renewable fuels rather than holding requirements flat over time. State-level policies, such as the Low Carbon Fuel Standard (LCFS) in California, are not modeled with as much detail as the federal RFS; however, in the case of California’s fuel policy, the applicable credit prices are determined endogenously, and do feedback into prices for biomass-based diesel fuels, leading to more or less incentive to expand the production and use of those fuels.

2.2. Data

Most of the historical data in the model are made publicly available by agencies within the U.S. Department of Agriculture (USDA), such as the Economic Research Service (ERS) and the Foreign Agriculture Service (FAS). Furthermore, fuel market data are primarily sourced from the Energy Information Administration (EIA) within the U.S. Department of Energy (DOE). Policy-specific information comes from the U.S. Environmental Protection Agency (EPA) and California’s Air Resources Board (CARB) for the RFS and LCFS, respectively. Price data related to these policies, like the prices for Renewable Identification Numbers (RINs) or LCFS credits, as well as many renewable product prices, are purchased directly from Oil Price Information Service (OPIS), a subscription-based service.

2.3. GHG Emissions Calculation

GHG emissions for each type of biodiesel: (1) FAME and (2) Renewable Diesel use in the U.S. were calculated based on California’s LCFS pathway-certified carbon intensities [25]. The GHG emission factors are differentiated by feedstocks used to produce each type of biodiesel. In our study, there were five types of feedstocks: (1) soybean oil, (2) corn oil, (3) canola oil, (4) used cooking oil, and (5) other fats and oil used in the production of renewable diesel, while FAME is derived from (1) soybean oil, (2) corn oil, and (3) canola oil. Based on the most recent U.S. EIA biomass-based diesel feedstock data, we estimated the portion of each feedstock utilized to produce FAME and renewable diesel that is domestically consumed within the U.S. [36].

The next step is to estimate the GHG emissions savings compared to the combustion of petroleum-based diesel fuel. We calculate the GHG emissions savings derived from the use of biomass-based diesel by feedstock and fuel type, FAME or Renewable Diesel, by subtracting the GHG emissions corresponding to the displaced petroleum-based diesel.

The results presented in later sections are, for the most part, projections determined endogenously within our modeling framework. However, the macroeconomic data that we use are exogenous. Both historical and projected macroeconomic data are purchased from S&P Global and incorporated into our model.

3. Results and Discussion

In terms of historical biomass-based diesel production, the U.S. produced FAME biodiesel almost exclusively. However, that has shifted since 2022 as renewable diesel (RD) production has increased dramatically. In 2023, 9.8 billion liters of renewable diesel were produced, which was around 1.5 times higher than the FAME production during the same year (as shown in Figure 1). The U.S. has also started producing sustainable aviation fuels (SAF), which are mainly produced from non-edible materials, including used cooking oil. In our outlook, we project continued growth in the production of biomass-based diesel, primarily from growth in both renewable diesel and SAF. This growth is somewhat offset by an initial decline in FAME production until 2030 before changes in the incentives to meet the RFS and LCFS requirements spur a recovery in FAME output. During the next 10 years, from 2025 through 2034, our study projects that renewable diesel production will grow by around 28% and SAF from barely 357 million liters to 3 billion liters, while FAME production will end around the same level as expected in 2024.

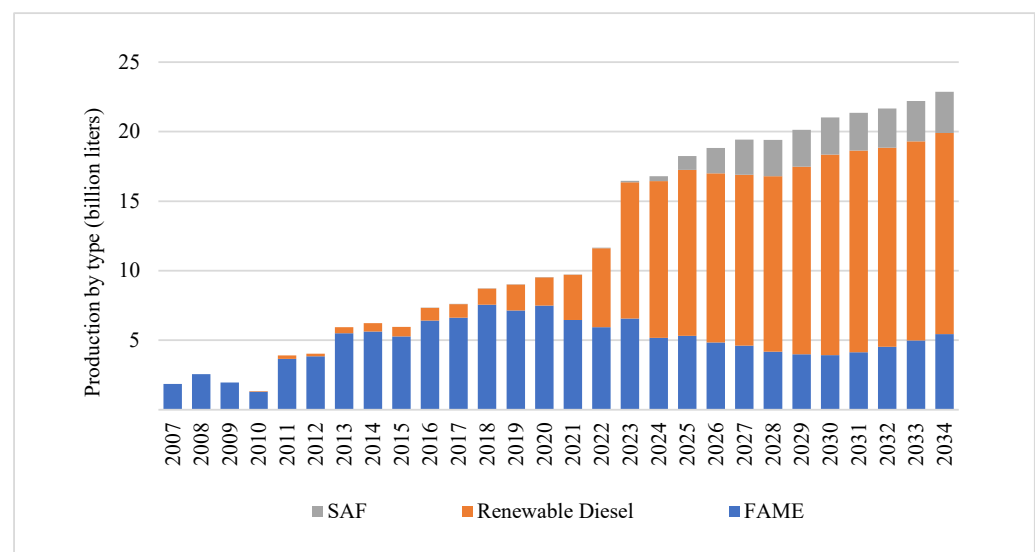


Figure 1. US biodiesel production by type: historical and projection. Source: Historical data from [23] and projections are from the authors' calculations.

As shown in Figures 2 and 3, the U.S. has seen a shift in the utilization of feedstock in the production of biomass-based diesel, as well. Until 2012, around 50% of the biomass-based diesel was produced from soybean oil, but by 2024, this share had fallen to 40%. During the same period, yellow grease (also known as used cooking oil) and other fats and oils used in renewable fuel production have increased substantially. Our 10-year projection also suggests the continuation of similar trends; the use of soybean oil increases by 37%, while the yellow grease and other fats and oil used in the production of biodiesel increases by around 80%.

In order to meet the goals laid out by policies such as the RFS at the federal level and the LCFS in states like California, Oregon, and Washington, the U.S. has substantially increased domestic consumption of biomass-based diesel over the last decade. From 2007 to 2024, the U.S. increased its biomass-based diesel consumption by 18 billion liters, which is approximately fourteenfold. Moreover, between 2022 and 2024, consumption increased by about 49%, mainly due to the increased domestic disappearance of renewable diesel in response to market incentives provided by federal and state-level renewable fuel policies. We project that the domestic consumption of biomass-based diesel will continue to increase, and from 2024 through 2034, it may grow by 23%, as shown in Figure 4. This expansion is primarily driven by the increasing use of renewable diesel to meet biomass-

based biodiesel-related RFS compliance volumes and carbon-intensity reduction targets in states like California, Washington, and Oregon.

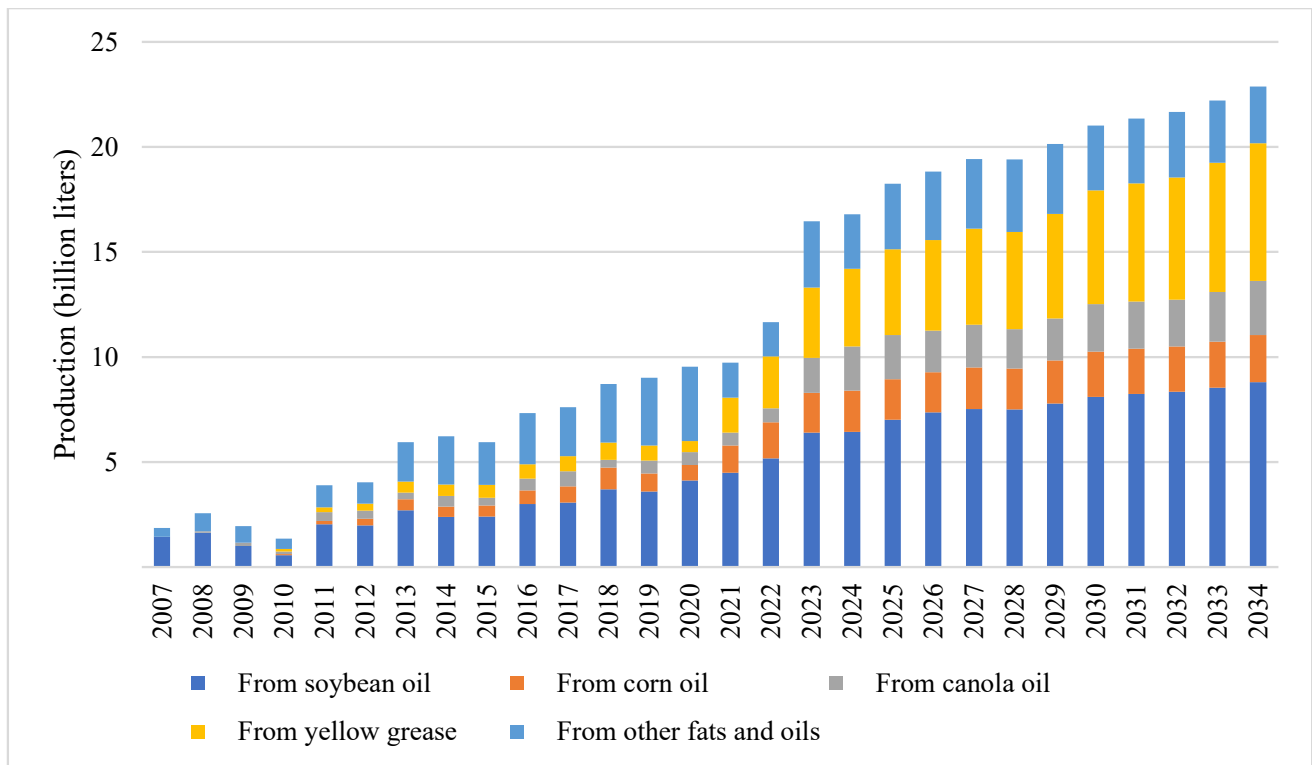


Figure 2. US biodiesel production by feedstock use: historical and projection. Source: Historical data from [23] and projections are from the authors' calculations.

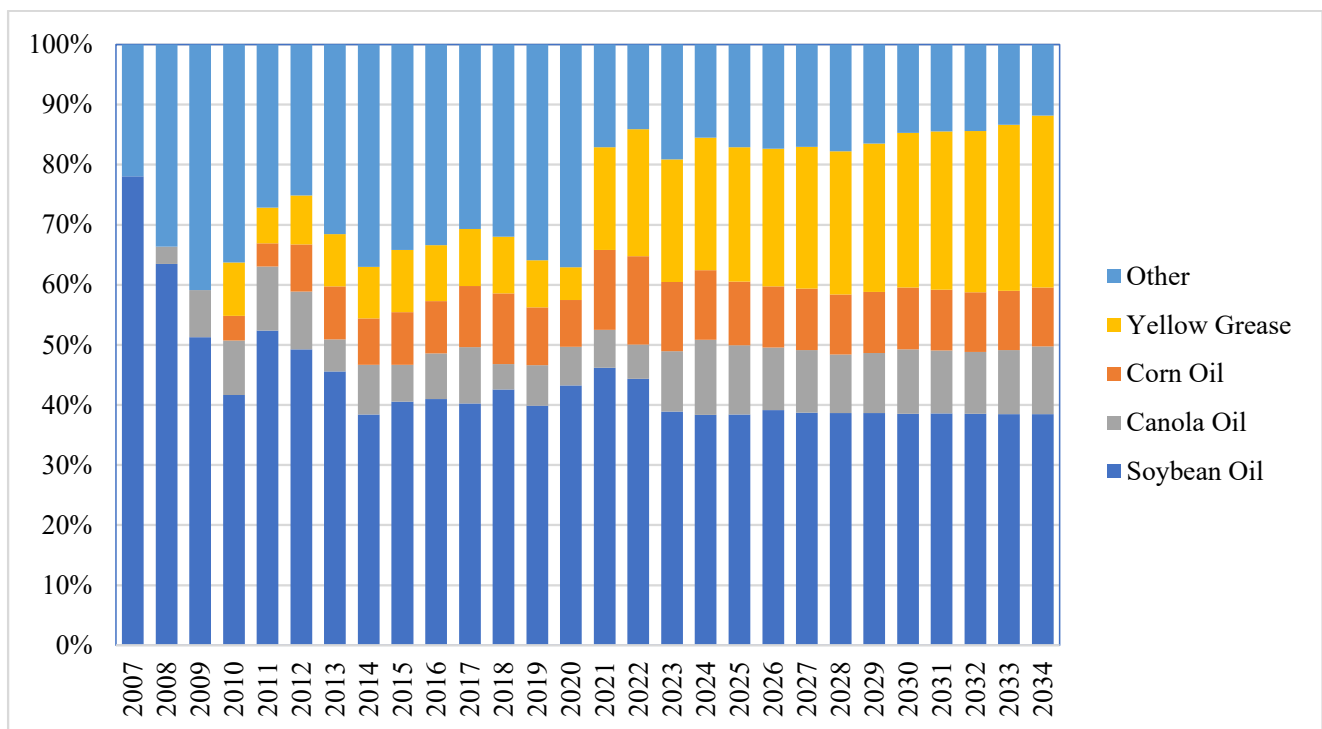


Figure 3. US biodiesel production by feedstock share: historical and projection. Source: Historical data from [23] and projections are from the authors' calculations.

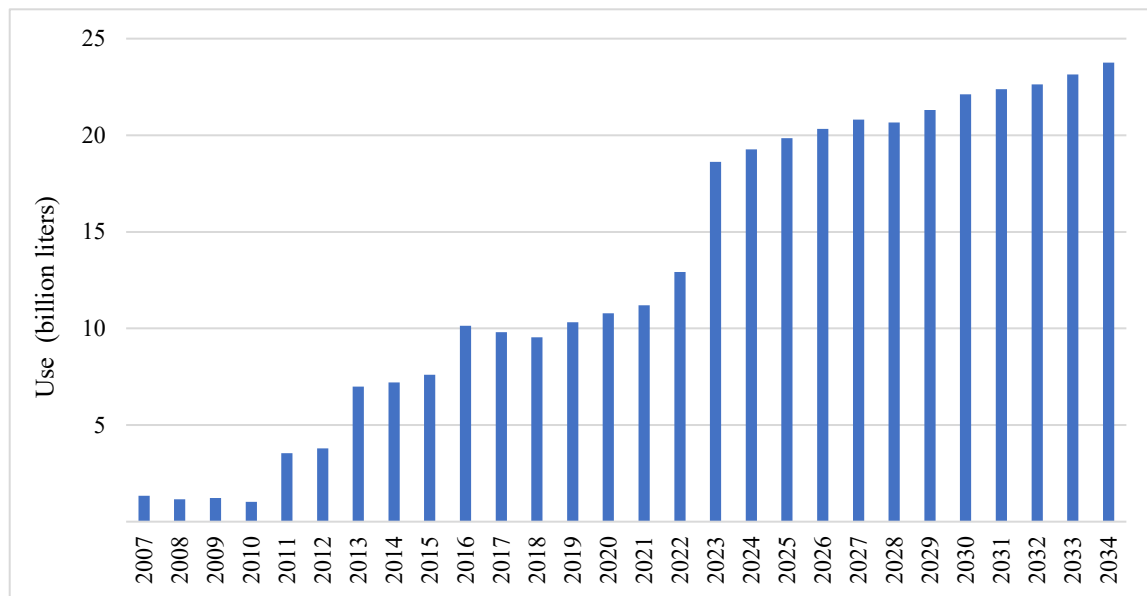


Figure 4. US total domestic biomass-based diesel use: historical and projection. Source: Historical data from [23] and projections are from the authors' calculations.

While the U.S. relied on the world biomass-based diesel market in the past to help meet its domestic biofuels mandate, that reliance has diminished somewhat in recent years. We further project that the overall imports of biomass-based diesel will continue to decline. Between 2024 and 2034, the net total imports decreased by 64%. Another major shift has happened; while historically, the U.S. imported FAME biodiesel, more recently, the imports have shifted toward renewable diesel. Although volatile, the U.S. biomass-based diesel trade is not large compared to domestic or world markets [35] (Figure 5).

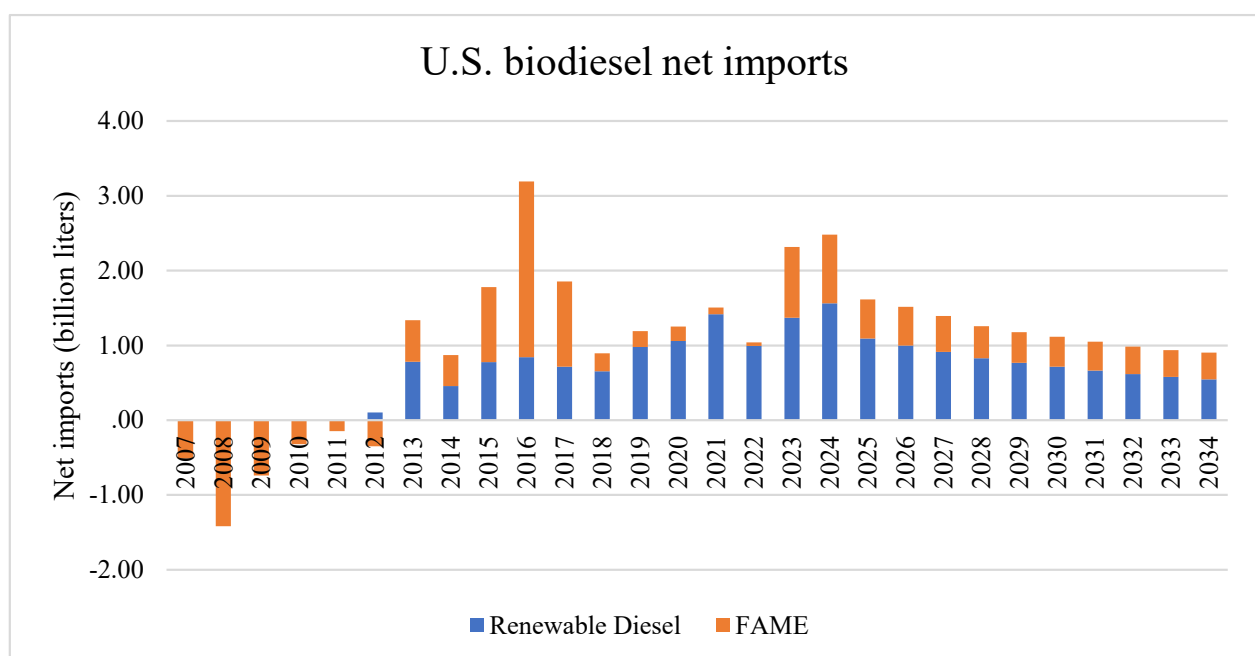


Figure 5. US net biodiesel imports by type: historical and projection. Source: Historical data from [23] and projections are from the authors' calculations.

GHG Emissions Saving

GHG emission reductions are often associated with legislated goals, and consequently, policy-relevant calculations might tend to draw on regulatory assessments of different

fuels and feedstocks. We use average rates of the LCFS and threshold values of the RFS to calculate emission reductions. The GHG emissions are calculated based on the emission assumptions outlined in Appendix A Tables A1 and A2. Figure 6a,b quantifies the GHG emission savings derived from switching from petroleum-based diesel to biomass-based diesel. We estimate that, over the next 10 years, the U.S. may save 238 billion kgCO₂e. We anticipate that most of the GHG savings are derived from using renewable diesel, which uses non-food-based feedstock, as shown in Figure 6b. Between 2025 and 2034, the use of renewable diesel derived from used cooking oil (UCO) and other non-food sources may reduce U.S. GHG emissions by 168 billion kgCO₂e. The GHG emissions reduction from the FAME during the same period also increased, which clearly shows that the U.S. is on the path of significantly increasing the use of sustainable fuels.

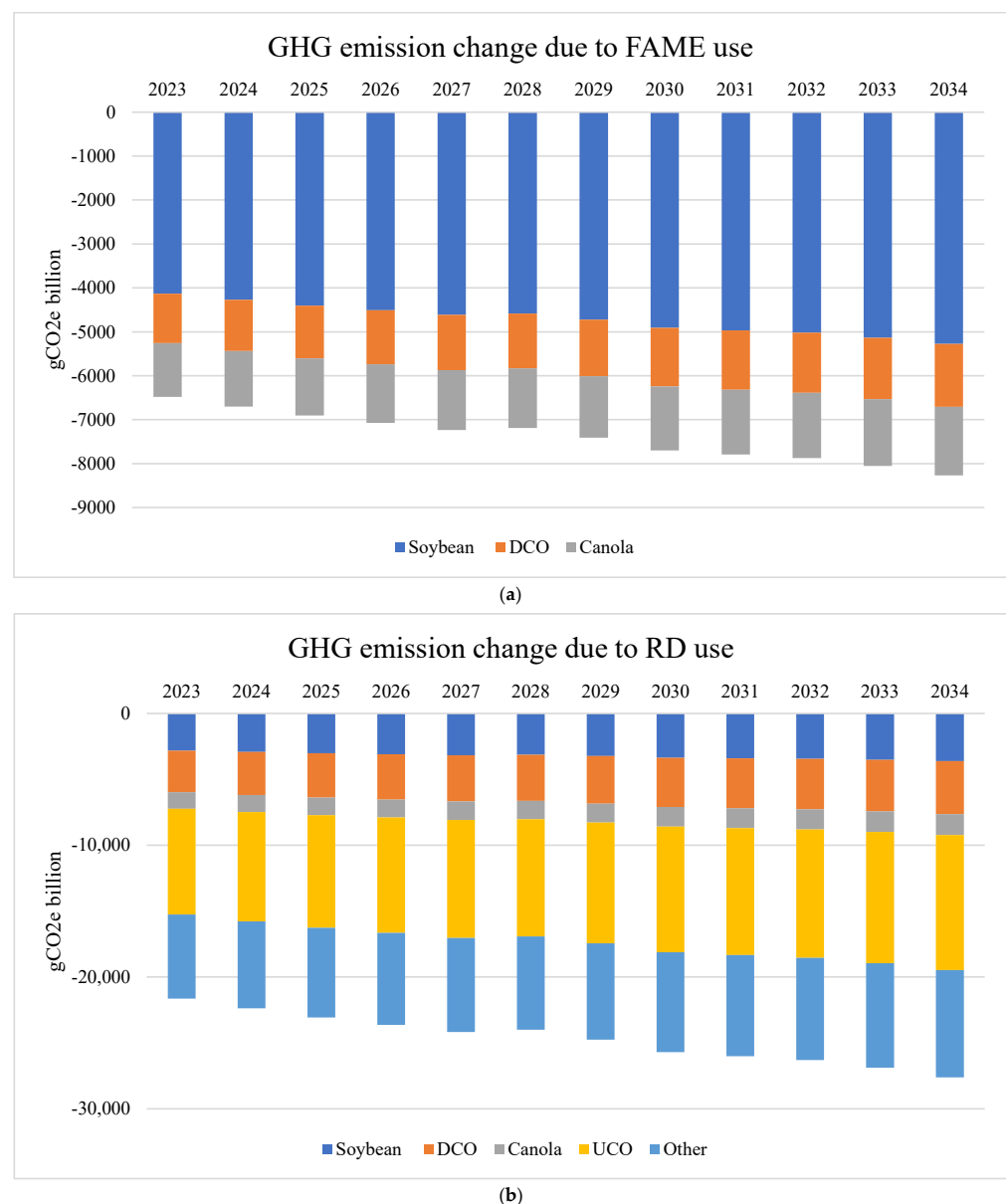


Figure 6. (a) US GHG emission saving due to the use of FAME. (b) US GHG emission saving due to the use of Renewable diesel (RD). Source: Carbon intensity scores from [25] and the authors' calculations.

4. Conclusions

New renewable fuels and new feedstocks production and use have surged lately, raising questions about the applicability of past studies and existing knowledge of these

fuels and the policies that support them. To the extent these patterns endure, or the changes continue, scientific assessment of biomass-based diesel's effects, such as on GHGs and food prices, will have to be updated to remain relevant to questions of sustainability. The U.S. case that we highlight validates our concerns. The stated purposes of the U.S. renewable fuel mandates, both at the federal and state levels, include reducing GHG emissions and serving the broader goals of environmental and economic sustainability, including limiting food price impacts. Such policies might be consistent with the United Nations' agreed-upon goals of working toward sustainable development. These new fuels and feedstocks could be important not only in the U.S. but also in the broader global agricultural commodity markets, GHG emissions, and sustainability more generally.

Biomass-based diesel use and production have shifted radically in recent years, and our results suggest that much of this change is permanent. The new context, with greater renewable diesel instead of biodiesel and more use of used grease or cooking oil as a feedstock relative to past shares, calls for an examination of these new feedstock-fuel pairs to understand their contributions toward these goals. Whereas biodiesel is chemically different from petroleum-based diesel, renewable diesel can substitute perfectly for the petroleum product in use, removing concerns about technical limitations of engines, temperature differences, or other factors that might be seen to limit the scope for biomass-based diesel to displace petroleum-based diesel. Feedstock composition has also undergone a sharp shift away from soybean oil, a vegetable oil that is made from soybeans and has many other uses, including food. In the place of the usual commercial oil feedstocks, yellow grease has become an important feedstock. The applicability of old studies to current and future decisions is impaired if they limit the potential to displace petroleum-based diesel or if they focus excessively on vegetable oil-based feedstocks of the past.

New fuels and new feedstocks cause new GHG emission impacts. Policy-relevant regulatory settings award a much lower GHG impact to biomass-based diesel made from yellow grease. Thus, with a greater scope for renewable diesel use relative to biodiesel in the past and with better regulatory assessments of GHG emissions from used cooking oil, the future patterns might differ from past trends and allow for greater GHG emissions from these fuels. We apply widely used techniques to analyze future market conditions to project biomass-based diesel and feedstock volumes. The structural economic model represents these supplies and demands, regulatory settings, and myriad-related agricultural commodity markets to capture many key interactions and complications. The results are contingent upon certain assumptions, such as normal weather and constant or announced policies, thus constituting projections given these conditions rather than predictions. However, the results suggest certain key future trends or pressures.

The results show a continued increase in renewable diesel use and a rising role of yellow grease as a feedstock in the next ten years. Perhaps surprisingly, however, the results also call for a stabilization of biodiesel production from soybean oil as policy incentives to shift away from such fuels wane in the future, at least slightly, according to policy changes. Biomass-based diesel consequently displaces additional petroleum-based products with greater contributions toward legislated GHG reduction targets over the next ten years. Given the stated intentions of the underlying policies and regulators' judgments about how different fuels help to meet these targets, the results suggest a rising role for biomass-based diesel relative to U.S. or even U.N. sustainability goals. For scientists, these complications about the mix of feedstocks and fuels can be reflected by considering how each might expand or contract depending on the market and policy context, enriching their analysis by differentiating among feedstock-fuel pairings.

The results also suggest some potential additional concerns or questions. The rising use of yellow grease as a feedstock is contingent on the future availability of this feedstock.

However, the supply of used cooking oil is quite unclear, as are the broader impacts. Should biomass-based diesel processors continue to rapidly expand their purchases of this feedstock, then is more used cooking oil generated by turning over grease more quickly, or by drawing yellow grease from other uses? More to the point, would either of these effects cause some positive demand impacts for other commercial vegetable oils, such as soybean oil, and cause price and production impacts to agricultural commodities indirectly? Another question focuses on the historically common fuels and feedstocks. If the existing policy setting implies that biodiesel and soybean oil feedstock volumes stabilize or recover, it might lead some observers to recall the food-versus-fuel debate and consider broader food price impacts. The projected volumes and GHG savings generated in this study suggest some continued and new patterns but also highlight key research questions that could help inform policymakers as they consider how best to achieve societal goals relating to sustainable economic growth.

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Institutional Review Board Statement: The IRB statement request is not relevant because our research data and methods do not require IRB approval.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. GHG emission by feedstock for alternative pathways for producing FAME biodiesel.

	Soybean	DCO	Canola	UCO	Other
	gCO ₂ e/MJ				
Mean	56.50	30.02	52.65	19.83	32.83
Standard Error	0.71	0.77	0.85	0.77	0.59
Median	55.41	29.12	52.25	20.78	32.50
Mode	54.50		53.00	21.00	28.90
Standard Deviation	3.88	3.79	4.26	7.42	4.34
Sample Variance	15.04	14.34	18.18	55.02	18.83
Kurtosis	1.71	−0.12	−0.43	24.30	−0.15
Skewness	1.12	0.69	0.52	−3.87	−0.08
Range	17.80	14.25	15.51	61.00	19.19
Minimum	50.03	24.50	46.43	−30.85	22.42
Maximum	67.83	38.75	61.94	30.15	41.61
Sum	1694.95	720.37	1316.37	1844.34	1805.52
Count	30.00	24.00	25.00	93.00	55.00

Source: Carbon intensity scores from [25] CARB (2024) and the authors' calculations.

Table A2. GHG emission by feedstock for alternative pathways for producing renewable diesel.

	Soybean	DCO	Canola	UCO	Other
	gCO ₂ e/MJ				
Mean	61.43	33.94	55.68	26.02	38.66
Standard Error	1.78	1.65	0.94	1.05	1.13
Median	60.50	32.50	55.11	26.00	38.66
Mode		32.50		26.00	37.00
Standard Deviation	7.36	6.61	2.49	5.76	8.13
Sample Variance	54.12	43.66	6.18	33.15	66.17
Kurtosis	4.72	4.63	0.83	−0.32	1.29
Skewness	1.90	1.96	0.99	0.38	−0.19
Range	32.02	25.99	7.33	22.88	45.31
Minimum	51.74	27.53	52.90	16.89	17.98
Maximum	83.76	53.52	60.23	39.77	63.29
Sum	1044.37	542.98	389.77	780.71	2010.49
Count	17.00	16.00	7.00	30.00	52.00

Source: Carbon intensity scores from [25] CARB (2024) and the authors' calculations.

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