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Policy Analysis

Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States

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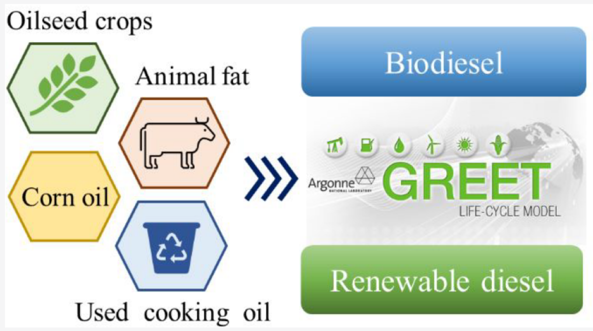
ABSTRACT: This study presents a life-cycle analysis of greenhouse gas (GHG) emissions of biodiesel (fatty acid methyl ester) and renewable diesel (RD, or hydroprocessed easters and fatty acids) production from oilseed crops, distillers corn oil, used cooking oil, and tallow. Updated data for biofuel production and waste fat rendering were collected through industry surveys. Life-cycle GHG emissions reductions for producing biodiesel and RD from soybean, canola, and carinata oils range from 40% to 69% after considering land-use change estimations, compared with petroleum diesel. Converting tallow, used cooking oil, and distillers corn oil to biodiesel and RD could achieve higher GHG reductions of 79% to 86% lower than petroleum diesel. The biodiesel route has lower GHG emissions for oilseed-based pathways than the RD route because transesterification is less energy-intensive than hydro-processing. In contrast, processing feedstocks with high free fatty acid such as tallow via the biodiesel route results in slightly higher GHG emissions than the RD route, mainly due to higher energy use for pretreatment. Besides land-use change and allocation methods, key factors driving biodiesel and RD life-cycle GHG emissions include fertilizer use and nitrous oxide emissions for crop farming, energy use for grease rendering, and energy and chemicals input for biofuel conversion.



KEYWORDS: *biodiesel, renewable diesel, greenhouse gas emissions, carbon intensity, life cycle analysis*

INTRODUCTION

Transportation is critical to enabling commerce, trade, and travel. However, it currently contributes about 29% of United States (U.S.) greenhouse gas (GHG) emissions,[1] because fossil fuels are the dominant transportation energy sources. Globally, the demand for liquid fuels is projected to increase by 32% between 2020 and 2050.[2] To stabilize the global climate within safe bounds, a transition from fossil fuels to sustainable energy resources is needed. To this end, sustainably produced biofuels can play a critical role in decarbonizing various transportation sectors.[3−5]

Biofuels are particularly important for hard-to-electrify transportation sectors with few other mature low-carbon technology options, such as long-haul trucks for freight, shipping, and aviation.[6−8] For road freight, blending biomass-derived diesel with petroleum diesel is one of the GHG mitigation strategies identified in earlier studies.[8−11] Currently, two major types of biomass-derived diesel are available in the market, including biodiesel (BD), or fatty acid methyl ester and hydrogenation-derived renewable diesel (RD), or hydro-processed esters and fatty acids. BD is produced via transesterification, whereas commercial RD production uses the catalytic hydro-processing method.

Recognizing the GHG mitigation potential, the production and consumption of biomass-derived diesel in the United States have been expanding steadily in the past decade. For instance, U.S. biodiesel production has increased 4-fold over the past decade from 0.34 billion gallons (1.30 billion L) per year in 2010 to more than 1.81 billion gallons (6.87 billion L) per year in 2020,[12] driven mainly by biofuel policies such as the federal Renewable Fuel Standard and California Low-Carbon Fuel Standard (LCFS). In recent years, the production and consumption of RD has also been expanding rapidly. RD is a drop-in biofuel in petroleum diesel without blending limitations. BD blending with petroleum diesel is limited in certain applications to an upper threshold (e.g., up to 20% by volume) without vehicle engine modifications. Since 2011, RD consumption has increased 300-fold in California[13] due to favorable policy incentives provided by LCFS.

Over the past decade, feedstocks used for BD and RD production in the U.S. have been more diversified. In addition to soybean oil and animal fats, low-value feedstocks such as used cooking oil (UCO) and distillers corn oil (DCO) are

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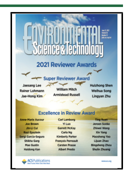

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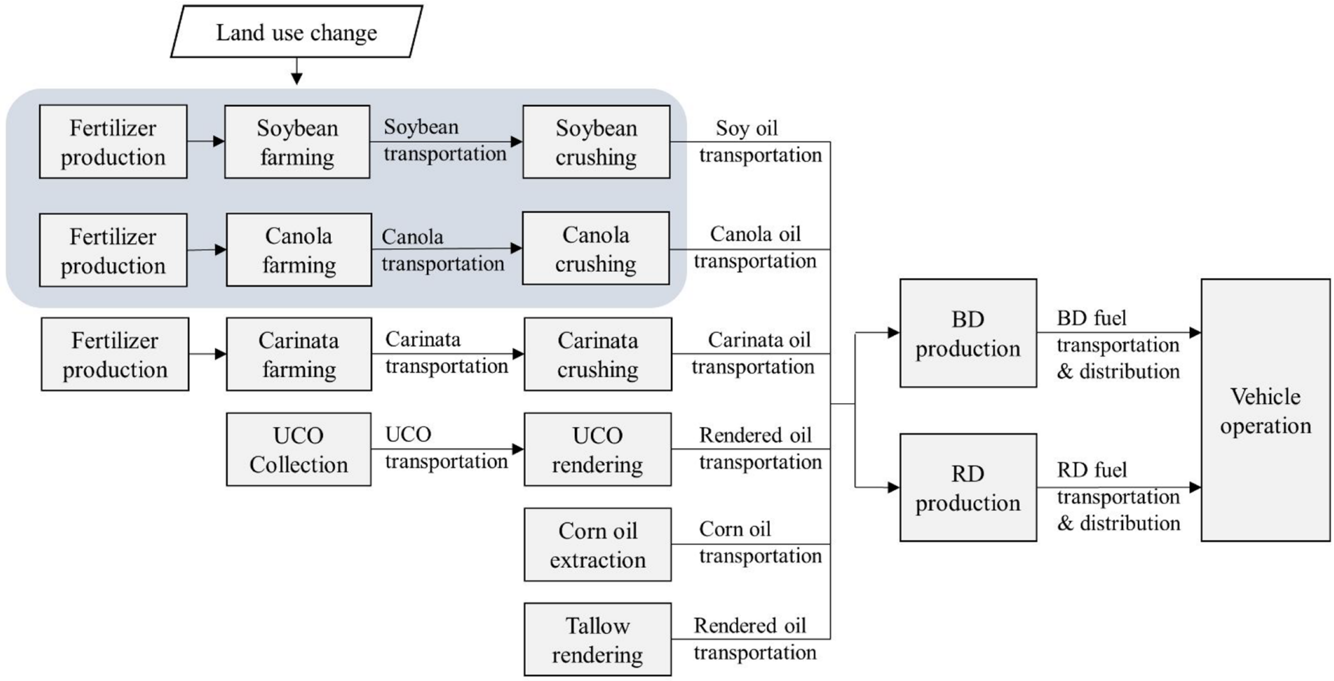

Figure 1. System boundaries for biodiesel (BD) and renewable diesel (RD) pathways. LUC-induced emissions are estimated for soybean- and canola-based pathways.

becoming prevalent. For instance, UCO and DCO share in U.S. biodiesel feedstock inputs increased from 11% in 2011 to 25% in 2019.[14] If all planned projects to expand U.S. RD production come online as intended, total U.S. RD production capacity will increase over 700% from 0.6 billion gallons (2.3 billion L) per year in 2020 to 5.1 billion gallons (19.3 billion L) by 2024.[15]

While domestic biomass-based diesel capacity is expanding rapidly and waste feedstocks are becoming prevalent, life-cycle analysis (LCA) based on real-world, commercial-scale BD and RD production data is lagging. Compared to the current assessment of BD and RD GHG emissions,[9,11,16−18] the novelty and contribution of this study lies in the following aspects. First, we developed detailed LCA models for several biomass to renewable diesel (RD) pathways with proprietary data collected from major biofuel producers. Biofuel LCA results are driven by data inputs, besides methodologies such as system boundaries and allocation methods. A common challenge for biomass to RD LCA is getting real-world data from commercial producers. As a workaround, studies had to use lab-scale data or process-based simulations,[11,19−21] with a few exceptions.[16,22] However, assumptions made in simulations can vary significantly from current industrial practices.[16] To inform evidence-based decision making, biofuel LCAs representing current industrial practices are needed. This study improves current LCAs of BD and RD GHG emissions by analyzing and synthesizing update-to-date proprietary data from major BD and RD producers in the United States. Second, our study models the real-world supply chain of waste feedstocks such as UCO. Residue and waste feedstock such as UCO is increasingly used for biofuel production, but current LCAs of UCO to BD and RD production in the United States do not sufficiently address GHG emissions arising from the UCO supply chain activities. This is mainly because data on UCO collection and processing is only sparsely available, partly because oil/fat rendering is a distributed business that involves many operators and facilities.

Considering the rapid pace of technology development for biomass-based diesel production and that biomass-based diesel will likely continue its fast-growing trend in connection with policies directed toward mitigating GHG emissions, an objective and updated life-cycle analysis (LCA) is needed to assess the carbon intensity of the U.S. biomass-based diesel industry and to inform sustainable expansion of the industry. This study aims to fill these gaps and investigate life-cycle GHG emissions of BD and RD production in the United States, incorporating the latest industry survey data sets covering the U.S. biomass-based diesel and fat rendering industries.

DATA AND METHODS

The Goal, Scope, and System Boundaries. The goal of this study is to provide updated life-cycle GHG emissions for BD and RD from the major feedstocks currently used in the United States. Biomass feedstocks considered in this study include virgin vegetable oils from soybeans (*Glycine max*), canola (*Brassica napus*), and carinata (*Brassica carinata*), as well as waste or byproduct feedstocks tallow, DCO, and UCO. Carinata is not currently used for commercial-scale BD and RD production in the United States. It is included here as a potential low-carbon, inedible feedstock. The functional unit is one megajoule (MJ) of BD and RD produced and used in vehicles.

The LCA is conducted using the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model developed at Argonne National Laboratory.[23] For both BD and RD pathways, well-to-wheels (WTW) GHG emissions are presented as grams of carbon dioxide equivalent per MJ (g CO_2e/MJ) of fuel consumed in a vehicle, which accounts for all energy and emissions associated with biofuel production and vehicle operation. We use the 100-year global warming potentials (GWP) from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5)[24] to calculate carbon dioxide equivalents.

The system boundaries of BD and RD pathways (Figure 1) vary based on feedstock types. Key stages for oilseed crops to BD and RD pathways include biomass production (i.e., farming), oilseed crushing and oil extraction, biofuel conversion, and fuel distribution and consumption. Key stages for tallow and UCO pathways include grease/oil rendering, biofuel conversion, and fuel distribution and consumption. In the U.S., beef tallow and white grease (rendered pork fat) contributed 57% and 31%, respectively, of the animal fats used for biofuel production.[25] Industrial data included in this study represent the beef tallow pathway. Tallow is a byproduct recovered from meat production processes and thus does not share upstream emissions (e.g., livestock cultivation). We further assume tallow is processed on-site because it is mainly sourced from meat processors, and an industrial survey by Argonne and North American Renderers Association (NARA) suggests that meat processors render tallow on-site. Survey results are summarized in the Life Cycle Inventory Data section. Still, third-party renderers can purchase meat by-products from meat processors for off-site rendering. However, data on transportation from meat plants to off-site rendering facilities are not available. For UCO, we also included collection and transportation activities because operators typically have to travel to multiple locations to fill up containers. The system boundary for DCO consists of separating DCO from distillers' grains and solubles (DGS) in corn ethanol plants. DCO is different from food-grade corn oil because it has high free fatty acids (FFA) content (9−16%) and is not suitable for human consumption. Edible corn oil is extracted from corn germs or whole kernels directly, and its FFA content is less than 0.5%.[26] In this study, DCO is considered a byproduct of corn ethanol production, and it does not share upstream emissions (e.g., corn farming) with corn ethanol. Feedstock classification (e.g., coproduct versus byproduct) determines which life-cycle stages would be included in the system boundary. While there is no universally accepted classification method, key criteria used in common classification methods include (1) the intention of the production of feedstock, (2) the economic value, and (3) the supply elasticity.[16] More information on feedstock classification methods can be found in Xu et al.[16] Here, we treat DCO as a byproduct by default because the main purpose of the ethanol refining process is to produce fuel ethanol. Also, DCO is a residual oil recovered from DGS, and its mass or revenue share is less than 5% in a typical dry mill ethanol plant (see SI: DCO share calculation). If DCO is not extracted, it will stay in DGS, which is typically used as animal feed. In the LCA of corn ethanol, this animal feed coproduct is typically treated with system expansions such that it provides a GHG credit to the ethanol equivalent to the impacts of producing the animal feed which would otherwise be required. In the GREET model, the credits are calculated based on the amount of corn and soybean meal that can be displaced by DGS. When DCO is recovered, it lowers DGS yield. Since less corn and soybean meal can be replaced by DGS, we reduced the GHG credits available to ethanol to reflect the consequences of DCO recovery.

During the vehicle operation stage, this study assumes carbon neutrality, which means CO_2 emissions from combustion of biomass-derived diesel are offset by CO_2 uptake from the atmosphere by plants. However, the CO_2 emissions from the combustion of the fossil carbon in the methanol used in BD production are included in BD combustion emissions. The GHG emissions associated with the construction of infrastructure for BD and RD facilities and other aspects of the supply chain are outside the scope of this analysis

Life Cycle Inventory Data. Life-cycle inventory (LCI) data sets used in this study include existing databases in GREET and additional data sets compiled from industrial surveys, government databases, and the literature. With support from National Biodiesel Board (NBB) and North American Renderers Association (NARA), Argonne conducted two industrial surveys to collect data sets from major BD and RD producers and oil/fat renderers in the United States. Due to the nondisclosure agreement, survey results from individual companies are not publicly available, but aggregated data are provided in the following sections.

Biomass to Vegetable Oil. Key parameters for crop cultivation include on-farm energy use, fertilizer inputs, and N_2O emissions from different sources (Table 1). We compiled

Table 1. Crop Yield, Farming Energy and Fertilizer Inputs, and N_2O Emissions (All in Dry Weight)

	soybean	canola	carinata
crop yield (kg oilseeds/hectare)	2961	1756	1871
energy input (MJ/kg oilseeds)			
diesel	0.42	0.59	1.73
gasoline	0.09		
natural gas	0.01	0.01	
liquefied petroleum gas (LPG)	0.03		
electricity	0.07	0.003	
fertilizer input			
nitrogen (g N/kg oilseeds)	1.85	56.45	26.08
phosphorus (g P_2O_5/kg oilseeds)	8.78	17.40	3.58
potassium (g K_2O/kg oilseeds)	13.92	4.55	0.51
herbicides (g/kg oilseeds)	0.82	0.46	2.66
insecticides (g/kg oilseeds)	0.01	0.04	0.35
N_2O emissions			
from N fixation: (g N_2O/kg oilseeds)[b]	0.23	-	-
N content in residue biomass (g N/kg oilseeds)	23.52	26.45	22.80
percentage of N in fertilizer released as N_2O	1.37%	1.04%	1.37%
percentage of N in biomass[a] released as N_2O	1.26%	0.94%	1.26%

[a]Including both above ground and below ground residue biomass. [b]N fixation is only relevant for soybeans, as canola and carinata are not legumes.

data on soybean yield and fertilizer inputs from USDA databases.[27] Additional data on soybean farming energy inputs for 2018, which were not published, were shared by the USDA Economic Research Service upon request.[27] Since canola is mainly cultivated in Canada, we use farming data for Canadian canola production in this study.[28] Data on carinata farming inputs were collected from the literature,[29,30] representing typical farming practices in the northern United States. More details on biomass feedstock cultivation LCI, including N_2O emissions, are provided in the GREET 2021 release technical report.[27]

We use the existing LCI database in GREET for the oilseed crushing stage. Energy and material balances for soybean crushing were extracted from a 2010 United Soybean Board

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report,[31] which was based on a 2008 industry survey conducted by the National Oilseed Processors Association (NOPA).[9] While NOPA is planning to conduct another industry survey, the 2010 report is still the latest database available to the public. Data on canola[32] and carinata oil[33] extraction were collected from the literature. In addition to crushing, energy use related to oilseeds and vegetable oil transportation is also included in this study, using existing transportation data in GREET.

Collection and Processing of Recycled and Low-Value Feedstocks (Tallow, UCO, and Corn Oil). We collected tallow and UCO rendering data (Table 2) with NARA support by surveying primary fat and grease renderers in the United States. The compiled LCI data sets represent industry average practices, covering 46 plants with tallow rendering operations and 61 UCO rendering facilities. The rendering plants included in this study either process beef byproducts only or predominantly use beef byproducts as raw material. Companies typically own several facilities, and most companies provide aggregate-level data instead of facility-level data to protect business-sensitive information. The tallow rendering process yields both rendered tallow and meat and bone meal (MBM), sold separately as animal feed ingredients.

Table 2. Inventory Data for Tallow and Used Cooking Oil (UCO) Rendering

	tallow	UCO, traditional	UCO, settling
feedstock input (kg/kg finished oil)	2.26	1.35	1.35
energy input (MJ/kg finished oil)	7.43	2.36	0.85
natural gas	4.99	2.11	0.76
animal fat	0.98	-	-
electricity	1.46	0.25	0.09
outputs (kg/kg finished oil)			
rendered fat/oil	1.00	1.00	1.00
meat bone meal (MBM)	1.04	-	-

There are no marketable coproducts from the UCO rendering process. The purpose of UCO rendering is to separate impurities and water from oil. In addition to the traditional UCO rendering method consisting of high-temperature cooking and tricanting, some renderers also use the so-called "settling" method to reduce energy demand. Instead of evaporating water in raw UCO via high-temperature cooking, raw UCO in settling plants is heated and then left to settle. Once settled, water is withdrawn from the tank, and UCO is subsequently recovered. NARA survey data show 25% of UCO renderers, representing 39% of facilities covered by the NARA survey, use settling as the primary method. Most companies use high-temperature cooking and tricanting.

We also collected transportation data (e.g., distance, mode, payload) for UCO (Table S1). Responses from companies indicate two primary UCO collection methods: direct route and bulk transfer. For the direct route method, trucks visit multiple locations along planned routes to fill up oil containers. On average, trucks need to travel 6.8 km to collect one ton of UCO. Once complete, they will return to the rendering facility directly. The total distance for a round trip is about 186 km on average. With the bulk transfer method, UCO collected from multiple individual trips/routes is aggregated at a bulk tank and then shipped to the rendering facility using heavy-duty trucks. The average distance from the bulk tank to rendering facilities is 124 km. Companies can use one or a mix of both collection methods. On the basis of survey responses, about 77% of UCO is collected via the direct route method, whereas bulk transfer contributes 23%.

For DCO, electricity use associated with separating corn oil (0.43 MJ/kg oil)[23] from distiller's grains and solubles, using a centrifuge, is assigned exclusively to DCO. In addition, transportation of DCO from ethanol plants to biodiesel plants is included in the analysis, using existing transportation data in GREET.

Biodiesel and Renewable Diesel Production. We summarized responses from the 2021 NBB industry survey to build LCI databases for BD production via transesterification and RD production via hydro-processing (Table 3). The NBB surveyed their membership for the purposes of this research. Thirty-eight producers were sampled, equaling 60 plants. The respondents include 27 plants, representing 45% of surveyed NBB plants. The data sets cover the production years 2018, 2019, and 2020. We processed inputs from the 27 plants (Table 3) to model typical commercial biodiesel production practices in the United States. The total BD production for the 27 plants which responded to the survey represents 60% of U.S. total biodiesel production.[34] Out of the 27 biodiesel plants, 13 processed vegetable oil (89.4 wt % soybean oil and 10.6 wt % canola oil) only, and the other 14 plants processed both vegetable oil and feedstocks with high FFA contents, including DCO, animal fat such as tallow, and UCO. On average, high FFA oils represent most (61 wt %) of the feedstock inputs in the 14 plants with mixed feedstock supply. This study uses data from the 13 vegetable oil processing plants to model soybean, canola, and carinata to BD pathways.

Table 3. Inventory Data for Biodiesel (BD) Production via Transesterification and Renewable Diesel (RD) Production via Hydro-Processing (per kg BD or RD)

	biodiesel		renewable diesel
	vegetable oil	high ffa oil	all pathways
feedstock input (kg/kg BD or RD)	1.00	1.05	1.26
energy use (MJ/kg BD or RD)			
natural gas	1.07	2.78	0.82
electricity	0.13	0.36	0.43
material inputs			
hydrogen (MJ/kg)	-	-	4.81
methanol (g/kg)	109	109	-
sodium hydroxide (g/kg)	1.07	-	-
sodium methoxide (g/kg)	3.62	-	-
hydrochloric acid (g/kg)	1.68	2.61	-
phosphoric acid (g/kg)	0.44	2.17	-
sulfuric acid (g/kg)	1.10	-	-
citric acid (g/kg)	0.003	-	-
sodium methylate (g/kg)	0.35	-	-
water consumption (L/kg)	0.15	0.99	-
outputs			
fuel (BD or RD, kg)	1.00	1.00	1.00
coproducts (fuel gas, LPG, and naphtha) (MJ/kg RD)	-	-	1.93
glycerin (100% pure, kg/kg BD)	0.10	0.07	-
FFA and distillation bottoms coproducts (kg/kg BD)	0.01	0.07	-

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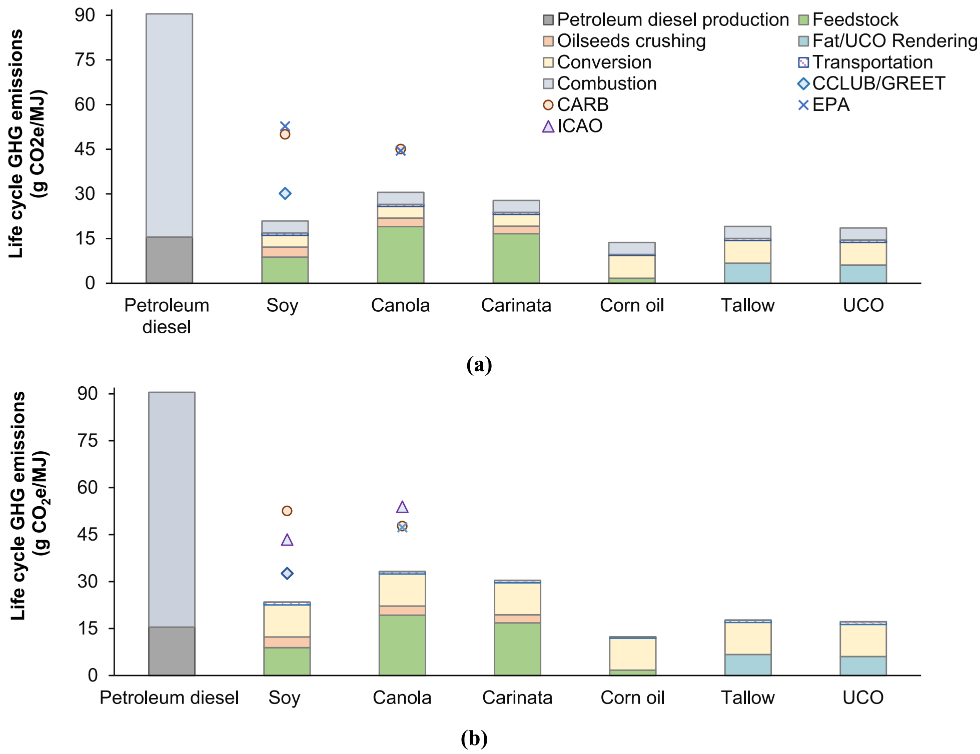

Figure 2. Life-cycle greenhouse gas (GHG) emissions of petroleum diesel versus (a) biodiesel (BD) and (b) renewable diesel (RD) pathways. Marker symbols represent life-cycle GHG emissions, including land-use change (LUC) emissions. UCO refers to used cooking oil. The rendering bar for UCO also includes UCO collection emissions. The corn oil pathway is based on distillers corn oil (DCO), not edible corn oil.

LCI data from the other 14 multifeedstock plants is used to model tallow, DCO, and UCO to BD pathways.

We constructed the LCI database for commercial RD production (Table 3) by compiling data from five different RD producers, including four U.S. companies and one international RD producer. The NBB industry survey mentioned above covers three RD producers, and we collected additional data points from petitions submitted to California's LCFS program. As of January 2021, there are only six commercial RD plants in the United States.[35] The RD LCI database we constructed includes four of the six RD producers. Because of the small sample, the participating companies request that we not release the exact feedstock composition and annual production information to protect the confidentiality and business-sensitive information. EPA's Renewable Identification Number (RIN) transactions data shows soybean RD and animal fats/UCO derived RD contributed 9.3% and 27.3% (volume basis) of total RD consumed in the U.S. in 2020.[36] While EPA does not provide a detailed breakdown for other feedstocks, data from the LCFS program indicate DCO is another important feedstock.[37]

Coproduct Allocation Methods. This study applied a process-level hybrid allocation method to attribute energy use and emissions to the different products from oilseed crushing, animal fat rendering, and biofuel conversion. A mass-based allocation was selected for both oilseed crushing and animal fat rendering, mainly because oilseed meals and MBM are protein or feed products rather than energy products.[9] The facilities are designed to separate incoming feedstocks into lipids and meals, and the mass balance is stable. We also applied market-based allocation to oilseed crushing and animal fat rendering as an alternative allocation method to test the sensitivity of results to a different coproduct allocation method. We use 10-year average prices to reduce the effect of price variability. An energy-based allocation method was used for RD production at the RD plants because coproducts from hydroprocessing, fuel gas, LPG, and naphtha, are also energy products. In contrast, the market-based allocation was applied to BD production at BD plants because the glycerine coproduct from the transesterification process is not an energy product.

Land-Use Change Emissions. LUC-induced emissions are also estimated for the oilseeds to BD and RD pathways (Table S2). We estimated LUC emissions using the CCLUB module in GREET for soybean oil-based pathways.[38] For soybean BD, the California Air Resource Board (CARB)-8 case was selected. Detailed discussions on LUC estimations, including comparison with alternative scenarios, can be found in Chen et al.[9] In this study, LUC emissions for soybean RD were converted from soybean BD LUC values after adjusting differences in biofuel yields (i.e., MJ of energy products produced from 1 kg of soybean oil). Alternative LUC emissions (Table S2) for soybean oil to BD and RD pathways, along with canola oil to BD and RD pathways, were collected from other studies, including those published by CARB, the International Civil Aviation Organization (ICAO), and the U.S. Environmental Protection Agency (EPA; Table S2). LUC from ICAO represent scenarios where biorefineries will produce both RD and renewable jet fuels. LUC values for carinata pathways are not available.

■ RESULTS

Life-Cycle GHG Emissions of BD and RD Pathways. Without including the LUC emissions, the WTW emissions of soybean, canola, and carinata oils to BD pathways (Figure 2a) range from 21 to 31 g of CO_2e/MJ, with soybean BD presenting the lowest value. The WTW emissions of the

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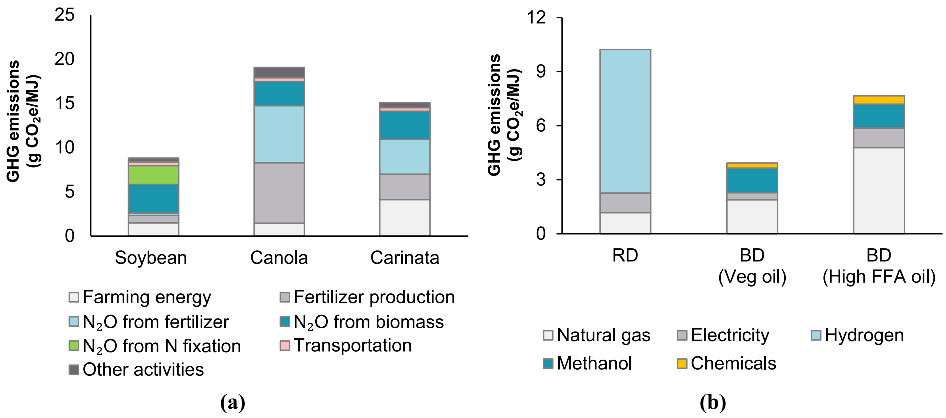

Figure 3. Breakdown of life-cycle greenhouse gas (GHG) emissions of (a) oilseed production and (b) biofuel conversion processes. FFA refers to free fatty acid. Other activities refer to GHG emissions associated with other farming activities, such as insecticides and CO_2 from urea application.

soybean, canola, and carinata oil to RD pathways are about 8–10% higher than their BD counterparts (Figure 2b). Depending on the LUC values, the WTW emissions of soybean oil and canola oil to BD and RD pathways with different LUC estimations (Table S2) may increase to 30 to 53 g of CO_2e/MJ (Figure 2).

The wide range of WTW emissions with LUC estimations reflects the significant variance in LUC estimations adopted by different organizations (Table S2). With GREET default LUC results, life-cycle GHG emissions of soybean BD and soybean RD would be around 30 and 33 g of CO_2e/MJ (Figure 2). GREET does not have LUC values for canola, and LUC estimations for carinata are not available. Tallow, UCO, and DCO pathways do not have associated LUC as these feedstocks are waste grease and byproducts.

Along with oilseeds to BD and RD supply chains, feedstock production and biofuel conversion are the two most essential stages, representing 61% to 88% of WTW emissions (Tables S3 and S4). The primary components contributing to feedstock production GHG emissions include N_2O emissions from fertilizer application and residue biomass, fertilizer manufacturing, and on-farm energy use (Figure 3a). For BD pathways, oilseed crushing, biodiesel conversion, and combustion contributions are comparable (Table S3). Compared to the BD route, conversion emissions for the RD route are 6.3 g of CO_2e/MJ higher, while contributions from farming and crushing stages are almost identical (Table S3 and S4). Although biomass input is higher for RD production, coproducts from hydroprocessing are also energy products (Table 3). After allocation, the feedstock burden is similar for both BD and RD pathways. A breakdown of BD and RD conversion emissions (Figure 3b) reveals that natural gas and methanol dominate BD conversion emissions, whereas hydrogen contributed 73% of hydro-processing GHG emissions. The GHG emissions associated with methanol input for transesterification are 83% lower than hydrogen input for hydroprocessing (Figure 3b).

The carbon intensity of BD is impacted by the fact that it contains fossil carbon originating from the conventional methanol used in BD production. Since BD includes fossil carbon from methanol, BD has higher combustion emissions than RD, which reduces net differences between BD and RD routes. Combustion emissions are not zero due to non-CO_2 emissions (e.g., methane, nitrous oxide) from fuel combustion and C embedded in fossil methanol inputs.

The life cycle GHG emissions of BD and RD from the waste feedstocks, tallow, UCO, and DCO are lower than the oilseed pathways, with results ranging from 12 to 19 g of CO_2e/MJ (Figure 2). The DCO pathways have the lowest emissions as corn oil does not share ethanol production emissions, whereas tallow and UCO-based pathways are close. For all three feedstocks, conversion is the stage with the most significant contribution for both BD and RD pathways (Figure 2). In theory, conversion emissions for hydroprocessing can vary slightly across feedstocks due to variations in fatty acids profiles,[39] if an RD plant uses a single feedstock. However, all commercial RD plants use a mix of multiple feedstocks, and conversion data for specific feedstock is not available. Here, we assume RD conversion emissions are the same for all feedstocks. While conversion emissions are the same for all RD pathways, biodiesel production using feedstocks with high FFA content presents significantly higher conversion emissions (7.7 g of CO_2e/MJ) than vegetable oil (3.9 g of CO_2e/MJ, Figure 3b). The additional natural gas demand needed for FFA treatment is the critical factor, resulting in 1.5 times greater natural gas use compared with vegetable oil conversion (Figure 3b). Collection and rendering is another critical stage for tallow and UCO-based pathways, representing about 35% of WTW emissions (Tables S3 and S4).

DISCUSSION

This study indicates that replacing petroleum diesel with BD and RD converted from oilseed crops and low-value feedstocks could significantly reduce GHG emissions. Without LUC emissions, the WTW GHG emissions of BD and RD produced from oilseed crops can be 63% to 77% lower than petroleum diesel. Soybean-based pathways present lower GHG emissions than canola and carinata because soybean farms have higher yields and lower fertilizer demand. Utilizing UCO, tallow, and DCO for BD and RD production could achieve even more significant GHG reductions (79% to 86% lower than petroleum diesel), mainly because they do not share emissions of upstream activities. LUC emissions will add 9.2 to 29 g of CO_2e/MJ to soybean oil and canola oil pathways, depending on the studies used for LUC estimations. With LUC emissions accounted for, life-cycle GHG emissions of soybean BD and RD could still be 64% to 67% (using GREET LUC value) or 42% to 52% (using LUC values from EPA, CARB, and ICAO) lower than petroleum diesel. Results with LUC emissions vary widely because both economic models and soil organic carbon

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modeling are subject to significant uncertainties,[40,41] even though both have been improved recently.[42] The uncertainties are due to differences in databases (e.g., baseline land-use data), model types, and critical assumptions (e.g., shock size); LUC modeling results can vary significantly across studies.[43]

Our results on soybean oil, canola oil, and tallow to BD pathways are comparable to those reported in previous studies.[9] While results for the canola pathway are close, GHG emissions of the soybean BD and tallow BD pathways are slightly lower than those reported in Chen et al.,[9] mainly due to lower soybean farming and tallow rendering emissions. Recently, Raizi et al.[11] estimated life-cycle GHG emissions of RD from soybean oil, tallow, and poultry fat. Compared to their results, the tallow RD pathway reported in this study has significantly lower GHG emissions due to large differences in rendering emissions. With the same allocation method, tallow rendering GHG emissions are about 13 g of CO_2/MJ lower in this study. The differences are likely driven by different data sources used for LCA. Results on soybean RD are more comparable. While our estimations for the feedstock stage are similar, conversion emissions are lower in this study, mainly due to different data sources used for RD conversion modeling.

Results on carinata pathways should be interpreted with caution since field trials and industrial scale-up of carinata for feedstock growth and biofuel production is still in the process. In northern states, carinata is typically planted as a scavenger crop to recover excessive nitrogen content. On the other hand, recent field experiments[44,45] in the southeast U.S. suggest that the fertilizer rate could be much higher if the objective maximizes biomass yield. Using recommended fertilizer rates[45] from trials conducted in the southeast U.S. would double carinata feedstock production GHG emissions. In this case, life-cycle GHG emissions of carinata BD and RD would increase by 11 g of CO_2e/MJ (Figure S1), but still more than 50% lower than petroleum diesel.

One of the contributions made in this study is providing more representative LCA results for tallow and UCO-based pathways by incorporating the latest industrial survey data. Compared to a 2018 LCA study[9] that utilized industrial data from Lopez et al.,[46] our results suggest rendering energy use for tallow has decreased by 20%. Meanwhile, animal fat rendering companies phased out residual oils and replaced them with natural gas (Table 2). Using the latest industrial data (Table 2), we found that GHG emissions associated with tallow rendering are 34% lower than the previous estimate.[9] While meat processors can render waste animal fat on-site, rendering companies must collect UCO from many locations. Our analysis reveals that UCO collection (Figure S2) represents 22% of total UCO collection and rendering emissions. During the UCO collection stage, GHG emissions estimated in this study are about half of that published by EPA,[47] but the WTW GHG emissions of UCO to the BD pathway evaluated in this study are 5.6 g of CO_2/MJ higher than EPA's estimation.[47] Since EPA did not provide different numbers for rendering versus biofuel conversions emissions, it is not clear which stage contributes the most significant difference. Compared to CARB's default numbers,[48] our estimations on UCO to BD and RD pathways are 7% and 28% lower due to lower emissions from rendering and conversion.

From a waste reduction and climate change mitigation perspective, recycling and converting waste greases to BD and RD could promote the circular economy and GHG reductions. Unlike edible vegetable oils (e.g., soybean oil), UCO and inedible tallow are recycled from waste streams, and DCO is extracted from the remaining stillage after ethanol distillation. Due to the high FFA content and other impurities, all three oils are unsuitable for human consumption and have lower market value than soybean oil. However, the supply of these feedstocks can be limited by the demand for the main products (e.g., meat, cooking oil).

Since waste grease is increasingly used for BD production, reducing energy use for FFA treatment would be critical to lowering life-cycle GHG emissions of waste grease to BD pathways. While vegetable oil to BD via transesterification could lower GHG emissions more than the RD route, GHG emissions of high FFA oil to BD pathways are higher than the RD route due to the extra energy required for FFA treatment. Furthermore, survey results suggest energy use at BD plants that process high-FFA oils have increased by 27% since 2015. Companies did not disclose the reason for the increase in energy use. Considering that BD yield at high-FFA oil plants increased by 5% since the 2015 survey, whereas BD yield at vegetable oil plants increased by only 1%, BD producers may have intensified the pretreatment step to convert FFA to BD via processes such as esterification or glycerolysis. Still, samples included in the 2015 and 2021 NBB surveys are not identical, so differences in data samples may also contribute to the higher energy use.

The selection of allocation methods may have significant impacts on biofuel LCA results (Figure S3). Applying market-value-based allocation to the oilseed crushing would increase soybean oil's share of farming and crushing emissions by 10% (Table S5). The increase reflects that the market price of soybean oil is higher than soybean meal on a mass basis.[49] In this case, life-cycle GHG emissions of soybean BD and soybean RD pathways would increase by about 5.7 g of CO_2e/MJ (Figure S3), and the increases come primarily from the farming stage (Figure S4). Changes in GHG emissions of canola BD and RD are more significant than soybean pathways (Figure S3) because farming emissions for canola are larger than soybean cultivation (Figure S4). Compared to mass-based allocation, using market-based allocation for oilseed crushing may be affected by market volatility. Conventionally, business decisions regarding oilseed crushing are mainly driven by the soybean meal and protein market,[50] because soybean oil accounts for only about 18% to 20% of the weight of soybean seeds.[51] Even though the market price of soybean oil ($0.77/kg, 2011−2020 average)[49] is higher than that of soybean meal ($0.41/kg, 2011−2020 average)[52] in the U.S. market, revenues from soybean meal still represent about 68% of revenues from whole soybeans. However, since late 2020, the soybean oil price has increased from $0.75/kg to $1.47/kg (Figure S5). With the recent market price, soymeal would represent about 52% of total revenues from soybeans. If the soybean oil price remains high in the coming years, using economic-based allocation will increase GHG emissions for soybean-oil-based BD and RD. The allocation method selected for the feedstock stage has a minor impact on waste oil and greases (Figure S3) because tallow and UCO do not share upstream farming emissions.

Compared to the allocation method, feedstock classification has a more significant impact on DCO-based pathways. If DCO is classified as a coproduct with ethanol in corn ethanol plants, DCO will share ethanol production and upstream corn farming emissions with ethanol. In this scenario, life-cycle

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GHG emissions of DCO to BD and RD pathways would be about 32 g of CO_2e/MJ higher (Figure S6), but they are still 50% lower than petroleum diesel.

Moving forward, the U.S. biomass-based diesel industry can take additional steps to achieve deeper GHG emissions reductions as part of the effort to decarbonize the transportation sector. The presented analysis can serve as a reference to identify critical areas with significant GHG reduction potentials. Our study reveals that crop production or farming is the most carbon-intensive stage for oilseeds to BD and RD pathways with current industry practices. Depending on the feedstock or crop used for BD/RD production, the composition of farming emissions can vary. On the other hand, recent studies suggested that a 71% reduction in GHG emissions from row crop agriculture is possible through novel and low-emission technologies.[53] When coupled with sustainable farming practices (e.g., cover crop) and increased soil organic carbon sequestration, there is a potential to produce net-zero or carbon-negative biomass feedstock. Replacing fossil energy and chemicals with low-emission alternatives would be the key to decarbonizing the biofuel conversion processes. For RD, the choice of H_2 production technologies can affect GHG results significantly. Replacing hydrogen made from natural gas with renewable hydrogen (e.g., electrolysis with nuclear power or wind power) could reduce RD emissions by 7.7 to 8.0 g of CO_2e/MJ (Figure S7). In contrast, if hydrogen is produced via coal gasification, RD emissions would increase by 6.5 g of CO_2e/MJ (Figure S7). For BD, if biobased methanol were used rather than conventional methanol, the carbon intensity of BD would reduce by 4.0 g of CO_2e/MJ. The rendering industry can also help with reducing feedstock carbon intensity. Taking UCO, the results are presented based on conventional rendering emissions and are modeled based on the conventional rendering method (Table 2). The settling method will reduce UCO rendering emissions by 64% (Figure S2). Follow on studies evaluating GHG reduction potentials of major BD and RD pathways and identifying strategies to accelerate the progress toward net-zero transportation would be beneficial to informing industry and policy decisions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c00289.

> Additional data sets for survey results, allocation factors, and life-cycle analysis results based on alternative allocation methods, including supporting figures and tables (PDF)

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Notes

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