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Development of emission parameters and net energy ratio for renewable diesel from Canola and Camelina

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ABSTRACT

This study estimated the greenhouse gas emissions (GHGs) and net energy ratio (NER) for producing hydrogenation-derived renewable diesel (HDRD) from canola and camelina in Western Canada. Using 1 MJ of energy in the HDRD produced as the functional unit, a variety of scenarios were evaluated to account for variations in allocation methods, co-products, oilseed yield, N_2O emission factor, and land use change (LUC). In producing HDRD, the farming stage and the oil conversion stage (i.e. the HDRD production stage) are the most energy and emission intensive. For canola based HDRD, the GHGs and NERs lie in the ranges of 33–94 gCO_{2e}/MJ and 1.2–2.2 MJ/MJ respectively. For camelina based HDRD, the GHGs and NERs range from 30 – 82 gCO_{2e}/MJ and 1.0–2.3 MJ/MJ respectively. In the base scenario (mass allocation; oilseed meal and propane fuel gas co-products; average yield; 0.76% N_2O emission factor; LUC ignored), HDRD from camelina (38 gCO_{2e}/MJ, 2.0 MJ/MJ) is environmentally superior to HDRD from canola (48 gCO_{2e}/MJ, 1.7 MJ/MJ) due to lower agricultural inputs and higher yield for camelina. Considering all of the scenarios examined, HDRD from both crops appears to be more sustainable than fossil diesel.

1. Introduction

Due to growing concerns over climate change and energy sustainability, many governments are creating policies to encourage development of alternative fuel sources. These policies often promote the use of biofuels (e.g. ethanol, biodiesel, and renewable diesel) as alternative fuels in the transportation sector because biofuels can be easily blended with conventional gasoline or diesel, and burned in unmodified engines. Since carbon contained in biofuels is originally derived from CO_2 in the atmosphere, biofuels are often said to be nearly carbon-neutral, that is, they contribute very little to the build-up of greenhouse gas emissions (GHGs) in the atmosphere.

Although biofuels are generally considered to be more sustainable than fossil fuels, there are three primary issues to consider if agricultural crops are used to produce fuel. First, the GHGs and energy inputs required to produce biofuels vary greatly with crop type and growing location. Second, if food crops are used to make biofuels, food prices can increase dramatically [1]. Third, increased demand for a particular crop can result in GHGs from land use change (LUC), where non-agricultural land (e.g. forest, grassland, or peat) is converted to agricultural land [2].

Due to these issues, a great deal of recent research has been dedicated to evaluating the sustainability of biofuels. To measure sustainability, life cycle GHGs and NER (i.e. net energy ratio, the ratio of energy output to fossil-fuel energy input) have been evaluated for a variety of biofuel pathways. For alternatives to fossil diesel, most of the available literature is focused on biodiesel from sunflower [3], palm [4,5], soybean [6–8], or canola/rapeseed [6,9–13]. In contrast, very few life cycle analyses (LCAs) have been completed for hydrogenation-derived renewable diesel (HDRD), which can be produced from the same feedstocks as biodiesel, but is closer in composition to fossil diesel and can have better cold flow properties than biodiesel [14–16]. Some authors have studied the sustainability of HDRD from rapeseed [17], soybean [14], and camelina [18], a promising low-input oilseed, but these studies are based in Europe or the United States. Although Canada is the world's largest exporter of canola oil [19], has conducted trials of growing camelina [20], and has implemented renewable fuels standards [21], no LCAs of HDRD from canola or camelina in Canada were available in literature. This study was an effort to fill a significant gap in the literature by evaluating the life cycle GHGs and NER of HDRD from canola and camelina in the Province of Alberta – one of the largest canola producing regions in Canada.

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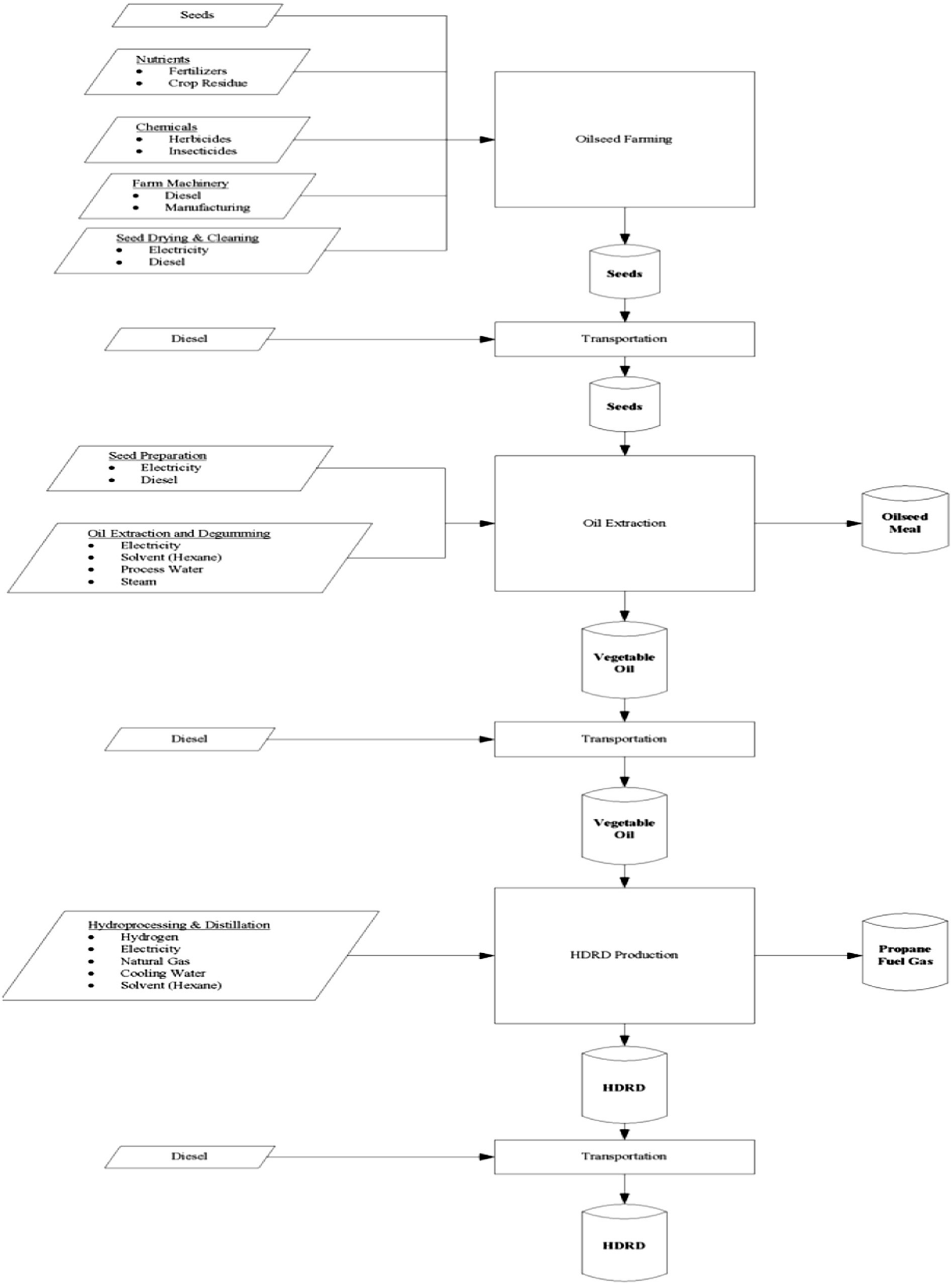

Fig. 1. System boundary for this LCA of HDRD production.

2. Methods

2.1. Scope

2.1.1. Goal definition

The goal of this study was to develop a data-intensive model to evaluate the sustainability of HDRD produced from canola or camelina in Alberta. GHG mitigation is the often the key driver behind government policies that promote renewable fuels, but NER (also known as energy output–input ratio or energy return on investment) is also important because it helps in understanding the effectiveness of energy use in producing a particular fuel [22]. Therefore, in this study, both life cycle GHGs and NER were estimated in order to quantify the sustainability of HDRD production. The key stages of HDRD production where emissions and energy consumption were estimated include: (i) oilseed farming, (ii) transportation of oilseeds to the oil extraction plant, (iii) oil extraction, (iv) transportation of oil to the HDRD plant, (v) HDRD production, and (vi) transportation of HDRD to the consumer.

Although a variety of LCA models exist in the public domain (e.g. GREET and GHGenius), the authors built a separate model for this study. The main driver to build a separate model was that it is not always clear where data is derived from in the publicly available models or how that data is used to calculate energy and emission impacts. Building a separate model also provided more flexibility to include site-specific data and data for pathway steps that were not available in the public models.

2.1.2. System boundary, functional unit and GHGs

Only direct inputs into each stage of HDRD production were considered for this LCA. That is, energy (e.g. diesel and electricity) and chemicals (e.g. fertilizers) consumed during HDRD production were considered direct inputs and were included in the LCA but other inputs such as the energy required to build the HDRD processing plant were considered indirect inputs and were not included in the LCA unless otherwise indicated. A schematic illustrating the system boundary for the LCA is given in Fig. 1. The functional unit used in this study is 1 MJ of energy in the renewable diesel produced (higher heating value basis), which is consistent with other studies [14,18,23,24]. The three primary gases considered for contribution to global warming were CO_2, CH_4, and N_2O, which have global warming potentials (CO_{2eq}) of 1, 25, and 298 respectively based on a 100 year time horizon [25].

2.1.3. Scenarios considered

Canola (*Brassica rapa* and *Brassica napus* L.) and camelina (*Camelina sativa*) were selected as feedstocks for this study because canola is widely grown in Alberta and camelina is an oilseed that is gaining attention as a feedstock for renewable fuel production [18,24,26–28]. Canola was developed from rapeseed, but has lower erucic acid and glucosinate content than traditional rapeseed. Camelina's main advantages over canola include a shorter growing season (less than 100 days), lower fertilizer inputs and water use, better cold tolerance, and fewer insect problems [29–31].

Although camelina has clear advantages over canola, unlike canola, the meal produced from camelina as a co-product in the oil extraction stage is not yet widely accepted as animal feed. Camelina has been approved by the US Food and Drug Administration for use as animal feed, but only up to 10% by weight for beef cattle and broiler chickens [32]. Inclusion (or exclusion) of camelina meal in energy and emission allocations has a significant impact on the results of the LCA and therefore a variety of scenarios were analyzed in this study – shown in Table 1.

The scenarios considered in this study were selected in order to account for variables (i.e. yield and field N_2O emissions) and methodological assumptions (i.e. co-products, allocation methods, and land-use changes) that could significantly impact the LCA results. Although HDRD and meal are the two products typically considered for HDRD LCAs, straw and propane are also produced in the process. Canola straw can be used for animal feed or bedding but has little feed value [33] and decomposes quickly, so it is less effective than wheat straw at preventing erosion if removed from the field [34]. Therefore, straw was only considered as a co-product in a sensitivity analysis rather than in the base scenario. Propane is produced at the HDRD plant during decarboxylation of the triglycerides in the vegetable oil. Propane can be used as fuel gas in the HDRD plant or steam-reformed to provide hydrogen for the process, thus it was included as a co-product in all of the sensitivity scenarios.

Allocation method is an important consideration for any LCA and several allocation methods are common in literature: energy allocation, displacement allocation (also known as system expansion), mass allocation, and economic value allocation. Energy allocation is often used for biodiesel or HDRD LCAs if the meal co-product from oil extraction is used as fuel in a boiler, but this practice is not common in Alberta. Displacement allocation accounts for changes in energy consumption and emissions by replacing equivalent products on the market with co-products [35]. In the case of biodiesel or HDRD LCAs in literature, soybean meal is usually the co-product that is displaced but in Alberta, soybeans are only grown on a limited basis [36] so this assumption is not realistic. Therefore, in this study, only mass and economic value allocation methods were used. Additional detail on allocation methods is available in literature [35,37].

In an effort to make the LCA calculations as transparent as possible, an attributional LCA model structure was used, in which each input to the process has an associated energy or emission coefficient [24]. These coefficients were obtained from published literature or calculated as indicated in the tables shown later in the

Table 1
Scenarios considered for the LCA.

Scenario	Crop	Allocation method	Products included	Yield	N_2O emissions (% of applied N)	Land use change considered?
Base	Canola, Camelina	Mass	HDRD, propane, meal	Average	0.76	No
1	Canola, Camelina	Mass	HDRD, propane, meal, straw	Average	0.76	No
2	Canola, Camelina	Economic value	HDRD, propane, meal	Average	0.76	No
3	Canola, Camelina	Mass	HDRD, propane, meal	Average	1	No
4	Canola, Camelina	Mass	HDRD, propane, meal	Average	2	No
5	Canola, Camelina	Mass	HDRD, propane, meal	Average	3	No
6	Canola, Camelina	Mass	HDRD, propane, meal	Average	4	No
7	Canola, Camelina	Mass	HDRD, propane, meal	Average	5	No
8	Canola, Camelina	Mass	HDRD, propane, meal	Average	0.76	Yes
9	Canola, Camelina	Mass	HDRD, propane, meal	Minimum	0.76	No
10	Canola, Camelina	Mass	HDRD, propane, meal	Maximum	0.76	No
11	Camelina	Mass	HDRD, propane	Average	0.76	No
12	Camelina	Economic value	HDRD, propane	Average	0.76	No

paper. To calculate the energy or emission impact for a particular input, the energy or emission co-efficient is simply multiplied by the input quantity and then converted to the functional unit basis.

2.2. Inventory assessment

2.2.1. Oilseed farming

As demonstrated by other studies [6,10,17], the agricultural stage has a significant impact on the life cycle GHGs produced and energy consumed in biodiesel and renewable diesel production. For canola and camelina farming, the main areas to consider include crop nutrients, chemicals, and seeding; machinery and fuel use; seed drying and cleaning; field N_2O emissions; and LUC emissions. The input quantities, energy and emission coefficients, and energy and emission impacts for these areas are summarized in Table 2a (canola) and b (camelina). Each area from Table 2a and b is discussed in more detail in the following subsections. Whenever possible, data specific to Alberta or Western Canada was used.

Table 2

Inputs, energy coefficients, emission coefficients, and impacts for a) Canola farming, base scenario and b) Camelina farming, base scenario.

Operation	Input quantity			Energy coefficients			Emission coefficients			Energy use (MJ/MJ)	Emissions (gCO_{2e}/MJ)
	Units	Used value	References	Units	Used value	References	Units	Used value	References		
a) Canola farming, base scenario											
Nutrients, chemicals & seeding											
Nitrogen	kg/ha	123.0	[38]	MJ/kg	49.45	[43]	gCO_{2e}/g	3.58	[43]	0.220	15.9
Phosphorous	kg/ha	14.5	[38]	MJ/kg	14.13	[43]	gCO_{2e}/g	1.07	[43]	0.007	0.6
Potassium	kg/ha	100.5	[38]	MJ/kg	8.84	[43]	gCO_{2e}/g	0.69	[43]	0.032	2.5
Sulfur	kg/ha	25.0	[38]	MJ/kg	11.26	[44]	gCO_{2e}/g	2.70	[47]	0.010	2.4
Crop residue	tonnes/ha	1.5	[39]	–	–	–	kg N/tonne	6.00	[48]	–	–
Herbicide	kg/ha	3.43	[40]	MJ/kg	267	[45]	gCO_{2e}/g	17.24	[45]	0.033	2.1
Insecticide	kg/ha	0.28	[41]	MJ/kg	285	[45]	gCO_{2e}/g	18.08	[45]	0.003	0.2
Seeds	kg/ha	6.55	[13]	MJ/kg	5.83	[9]	gCO_{2e}/g	1.19	[9]	0.001	0.3
Machinery & fuel use (diesel)											
Manufacturing & maintenance	–	–	–	MJ/ha	1456	[12]	gCO_{2e}/ha	35,740	[12]	0.053	1.3
Sowing	L/ha	10	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.016	1.2
Farm chemical spraying	L/ha	4	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.007	0.5
Spreading fertilizer	L/ha	14	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.023	1.7
Harvesting	L/ha	25	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.041	3.0
Seed transportation	L/ha	8	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.013	1.0
Seed drying and cleaning											
Electricity	kWh/tonne seed	11.0	[9,12]	MJ/kWh	9.89	[46]	gCO_{2e}/kWh	880	[50]	0.005	0.5
Diesel	L/tonne seed	1.2	[12]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.003	0.2
Field emissions											
N_2O emissions	–	–	–	–	–	–	% as N_2O-N	0.76	[13]	–	17.0
Land use change											
N_2O credit	–	–	–	–	–	–	g N_2O/ha	−503	[51–53]	–	–
Change in soil nitrogen	–	–	–	–	–	–	g N_2O/ha	1138	[51,60]	–	–
Change in soil carbon	–	–	–	–	–	–	kg CO_2/ha	3187	[51,60]	–	–
Farming subtotal										**0.47**	**50.4**
b) Camelina farming, base scenario											
Nutrients, chemicals & seeding											
Nitrogen	kg/ha	92.5	[20,24]	MJ/kg	49.45	[43]	gCO_{2e}/g	3.58	[43]	0.176	12.8
Phosphorous	kg/ha	39.9	[24,54]	MJ/kg	14.13	[43]	gCO_{2e}/g	1.07	[43]	0.022	1.6
Potassium	kg/ha	38.9	[24,54]	MJ/kg	8.84	[43]	gCO_{2e}/g	0.69	[43]	0.013	1.0
Sulfur	kg/ha	0.0	[24]	MJ/kg	11.26	[44]	gCO_{2e}/g	2.70	[47]	0.000	0.0
Crop residue	tonnes/ha	1.5	[39]	–	–	–	kg N/tonne	6.00	[48]	–	–
Herbicide	kg/ha	0.7	[24]	MJ/kg	267	[45]	gCO_{2e}/g	17.24	[45]	0.008	0.5
Insecticide	kg/ha	0.0	[24]	MJ/kg	285	[45]	gCO_{2e}/g	18.08	[45]	0.000	0.0
Seeds	kg/ha	8.0	[24]	MJ/kg	2.35	[24]	gCO_{2e}/g	0.39	[24]	0.001	0.1
Machinery & fuel use (diesel)											
Manufacturing & maintenance	–	–	–	MJ/ha	1456	[12]	gCO_{2e}/ha	35,740	[12]	0.056	1.4
Sowing	L/ha	10	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.017	1.3
Farm chemical spraying	L/ha	4	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.007	0.5
Spreading fertilizer	L/ha	14	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.024	1.8
Harvesting	L/ha	25	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.044	3.2
Seed transportation	L/ha	8	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.014	1.0
Seed drying and cleaning											
Electricity	kWh/tonne seed	11.0	[9,12]	MJ/kWh	9.89	[46]	gCO_{2e}/kWh	880	[50]	0.008	0.7
Diesel	L/tonne seed	1.2	[12]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.004	0.3
Field emissions											
N_2O emissions	–	–	–	–	–	–	% as N_2O-N	0.76	[13]	–	13.9
Land use change											
N_2O credit	–	–	–	–	–	–	–	–	–	–	–
Change in soil nitrogen	–	–	–	–	–	–	–	–	–	–	–
Change in soil carbon	–	–	–	–	–	–	–	–	–	–	–
Farming subtotal										**0.39**	**40.2**

Note that all of the energy and emission impacts given in Table 2a and b are for the base scenario from Table 1, which means that LUC was not included and average yields were used. The minimum, average, and maximum gross and net yields considered for canola and camelina in this study are shown in Table 3. For canola, the yields are based on a 12-year average from 1997 to 2008 [36,55,56] and for camelina, the yields are based on trials conducted by Agriculture and Agri-Food Canada [20].

2.2.1.1. Crop nutrients, chemicals, and seeding. The primary nutrients considered in this study for canola and camelina growth were nitrogen, phosphorous, potassium, and sulfur. The input quantities of these nutrients for canola were provided by the Canola Council of Canada as average application rates in Canada [38]. Data regarding nutrient application rates for camelina is more scarce than data for canola and was derived from a few different sources [20,24,54]. As noted by Sultana and Kumar [39], "lime is usually applied to acidic soil to neutralize [excess acidity] but only 5% of the total area of Alberta lies in the acidic region", therefore lime application was not considered here. In general, canola requires more synthetic fertilizers than camelina, which results in higher energy and emission impacts for canola.

Additional nutrients for crop growth are supplied by crop residues left from the previous harvest; canola and camelina can be rotated with cereal crops such as wheat and barley so the quantity of crop residue left on the field was based on typical wheat crop residues for Western Canada. Crop residues do not contribute to energy use but do contribute to N_2O emissions from the field since part of the nitrogen in the crop residues is converted to N_2O as they decompose.

Other chemicals needed for crop growth are herbicides and insecticides. As was the case for synthetic fertilizers, canola requires more herbicides and insecticides than camelina, which results in greater energy use and emissions. The seeding rates for canola and camelina are similar and were taken from previous studies [13,24].

2.2.1.2. Machinery and fuel use. Diesel fuel is consumed for farming operations such as sowing, spraying chemicals, spreading fertilizer, harvesting, and seed transportation. Input quantities for each of these operations for canola farming were taken from Baquero's LCA study [42]. Due to a scarcity of data, the same input quantities (on a per ha basis) were used for camelina and the energy and emission impacts for these inputs were adjusted based on camelina's yield. Since energy and emission parameters were available for farm equipment manufacturing (an indirect input), these were included in the LCA.

2.2.1.3. Seed drying and cleaning. Before being transported to the oil extraction plant, seeds often go through a preliminary drying and cleaning step, which requires electricity and heat. The energy requirements for drying are based on drying the seed to 8% moisture content.

2.2.1.4. Field N_2O emissions and land use changes (LUC). Two of the largest and most contentious sources of emissions for agricultural-based renewable fuels are the emissions that come from soils (field emissions) and the emissions that result from LUC. For field emissions, the main concern is N_2O that is released due to nitrification and denitrification processes in the soil [58]. Using the Intergovernmental Panel on Climate Change (IPCC) guidelines [58], direct N_2O emissions can be calculated based on the quantity of nitrogen added to the soil from a variety of sources such as synthetic fertilizers, organic fertilizers, and crop residues. Based on the 2006 IPCC guidelines, Equation (1) shows how direct N_2O emissions were calculated for canola and camelina farming in this study.

Table 3
Yields and loss factors for Canola and Camelina.

Factor	Canola	Camelina	Units	References
Gross yield (min, avg, max)	1.21, 1.66, 2.12	1.53, 2.25, 4.15	tonnes/ha	[20,36,55,56]
Harvesting loss	0.1	0.1	tonnes/ha	[31]
Dockage loss	9%	9%	percentage	[38,57]
Handling loss	2%	2%	percentage	[31]
Net yields (min, avg, max)	0.99, 1.39, 1.80	1.28, 1.92, 3.61	tonnes/ha	Calculated

$$N_2O_{\text{direct}}\text{-N} = (F_{SN} + F_{ON} + F_{CR} + F_{SOM})*EF_1 \quad (1)$$

where N_2O_{direct}-N: annual direct N_2O-N emissions produced from managed soils, kg N_2O-N/yr; F_{SN}: amount of synthetic fertilizer N applied to soils, kg N/yr; F_{ON}: amount of organic N additions applied to soils, kg N/yr (zero for this study); F_{CR}: annual amount of N in crop residues returned to soils, kg N/yr; F_{SOM}: annual amount of N in mineral soils that is mineralized in association with a loss of soil C as a result of changes to land use or management, kg N/yr (addressed with LUC); EF_1: emission factor for N_2O emissions from N inputs, kg N_2O-N/kg N input.

The default emission factor for amount of nitrogen added to soil that is evolved as N_2O-N is 1%. However, this emission factor is very site-specific, and can vary significantly depending on climate, type of crop, type of soil, and tillage methods [11,39]. In this study, an Alberta-specific emission factor of 0.76% [13] was used in the base scenario, but some authors have contended that the direct N_2O emission factor can be as high as 5% [59]. Therefore, scenarios 3–7 (see Table 1) were developed to account for the variety of emission factor estimates.

The IPCC has also published guidelines regarding methods to calculate soil emissions that result from land use changes [60]. In general, when land changes from one use (e.g. natural grassland) to another (e.g. cropland), the carbon and nitrogen stock (i.e. amount of carbon and nitrogen stored in the soil) gradually changes until a new equilibrium has been established. It can take 20 years or more to establish the new equilibrium and the new equilibrium level depends on initial and final land use types, climate zone, soil management, and input of organic matter [60]. Based on the 2003 IPCC guidelines, Equations (2) and (3) show how changes in soil carbon stock were calculated in this study. After calculating soil carbon stock, soil nitrogen stock was calculated using a carbon to nitrogen ratio of 15.

$$\Delta C = \left[\left(SOC_o - SOC_{(o-T)}\right)*A\right]\Big/T \quad (2)$$

where ΔC: annual change in carbon stock, tonnes C/yr; SOC_o: soil organic carbon stock in the inventory year, tonnes C/ha; $SOC_{(o-T)}$: soil organic carbon stock T years prior to the inventory, tonnes C/ha; T: inventory time period, yr (default is 20 years); A: land area of each parcel, ha

$$SOC = SOC_{REF}*F_{LU}*F_{MG}*F_I \quad (3)$$

where SOC_{REF}: the reference carbon stock, tonnes C/ha; F_{LU}: stock change factor for land use or land use change type, dimensionless; F_{MG}: stock change factor for management regime, dimensionless; F_I: stock change factor for input of organic matter, dimensionless.

When LUC was considered in this study, only the GHGs from canola HDRD were impacted. As noted by other authors [18,24], camelina does not deplete soil nutrients nearly as much as other crops, so camelina could potentially replace the fallow stage in a typical 3 or 4-year crop rotation of oilseeds with cereals. Therefore, if vegetable oil for renewable fuel production comes from camelina,

Table 4
Factors used to calculate LUC emissions from changes in soil nitrogen and carbon content.

Factor	Factor description	Value	Units	References	Comments
Grassland (natural vegetation)					
F_{LU}	Land use factor	1	N/A	[60]	Default value
F_{MG}	Management factor	1	N/A	[60]	Nominally managed (non-degraded)
F_I	Input factor	1	N/A	[60]	Nominal
SOC	Soil organic carbon stock	39	tonnes C/ha	[51,60]	Average of clay and sandy soils. See IPCC pg 3.117
BOC	Biomass organic carbon stock	4.2	tonnes C/ha	[60]	Cold temperate, dry and using root to shoot ratio. See IPCC pg 3.109–3.110
TOC	Total organic carbon stock	43.2	tonnes C/ha	Calculated	
C:N	Carbon to nitrogen ratio	15.0	N/A	[60]	See IPCC pg 3.94
TN	Total nitrogen stock	2.9	tonnes N/ha	Calculated	
Canola cropland					
F_{LU}	Land use factor	0.7	N/A	[60]	Long term cultivated
F_{MG}	Management factor	1.05	N/A	[38,60]	Reduced tillage
F_I	Input factor	0.9	N/A	[60]	Low
SOC	Soil organic carbon stock	25.8	tonnes C/ha	[51,60]	Average of clay and sandy soils. See IPCC pg 3.117
BOC	Biomass organic carbon stock	0.0	tonnes C/ha	[51]	Most vegetation removed, therefore assume zero.
TOC	Total organic carbon stock	25.8	tonnes C/ha	Calculated	
C:N	Carbon to nitrogen ratio	15.0	N/A	[60]	See IPCC pg 3.94
TN	Total nitrogen stock	1.7	tonnes N/ha	Calculated	
Emissions from change in carbon stock					
T	Time period	20	years	[60]	Default value
CC	Carbon conversion	3.67	kg CO_2/kg C	Calculated	Based on molar properties
CO_{2E}	Carbon dioxide emissions	3187	kg CO_2/ha yr	Calculated	
Emissions from change in nitrogen stock					
T	Time period	20	years	[60]	Default value
NC	Nitrogen conversion	1.57	kg N_2O/kg N	Calculated	Based on molar properties
EFN	Nitrous oxide emission factor	1.25	kg N_2O-N/kg N	[60]	See pg 3.94
NE	Nitrous oxide emissions	1.1	kg N_2O/ha yr	Calculated	

it may not be necessary to convert non-agricultural land to agricultural land, meaning that LUC emissions are not introduced. On the other hand, if canola oil were to be used for large volumes of renewable fuel production, new agricultural land would likely need to be developed because most of the canola oil currently produced in Alberta is used in the food industry.

When including LUC in this study, it was assumed that grassland under natural vegetation was converted to cropland for farming canola. The values used for the parameters in Equations (2) and (3), as well as other factors used in the LUC calculations are given in Table 4. Note that although N_2O and CO_2 are released when grassland is converted to cropland, grassland under natural vegetation produces a baseline level of N_2O [51–53], which can be considered an emissions credit in the LUC calculation (−503 g N_2O/ha for this study).

2.2.2. Transportation of oilseeds from the field to the oil extraction plant

After the oilseeds have been harvested, they are transported from the field to the oil extraction plant. In this LCA, it was assumed that seeds are transported from the field to the oil extraction plant by trucks with a capacity of 27 tonnes [12], full-load fuel consumption of 0.35 L/km [61], and empty-load fuel consumption of 0.28 L/km [61]. The field-to-plant transportation distances are based on previous work done by the authors [31], in which they determined the economically optimal sizes of canola and camelina oil extraction plants for Alberta (190 million L/year for canola and 120 million L/year for camelina); these plant sizes were used as the basis for this LCA, which resulted in a round-trip seed transport distance of 164 km for canola and 132 km for camelina. The energy and emission coefficients used for seed transportation were 45.25 MJ/L of diesel [46] and 3336 gCO_{2e}/L of diesel [45,49] respectively. Overall, seed transportation has a very small impact on both energy use (0.004 MJ/MJ for canola, 0.005 MJ/MJ for camelina) and emissions (0.3 gCO_{2e}/MJ for canola, 0.4 gCO_{2e}/MJ for camelina).

2.2.3. Vegetable oil extraction

At the oil extraction plant the seeds are typically dried and cleaned, then the oil is extracted by crushing the seeds with a press and then using a solvent (hexane) to absorb residual oil from the oilseed meal [62]. After extraction, the oil is degummed to remove phosphatides, which prevents sludges from forming during storage [62]. Although the degumming stage for camelina is slightly different than it is for canola (e.g. different chemicals used to induce phosphatide precipitation), the preparation, pressing, and solvent-extraction stages are the same for both crops [63]. Canola seeds contain approximately 44% oil by mass [64], and estimates for camelina seed oil content range from approximately 30% [65] to 38% [66]. To remain consistent with the authors' previous work [31], an oil content of 30% for camelina was used in this LCA.

In published literature, detailed input quantity data for canola and camelina oil extraction is very scarce. Of the studies that listed input quantity data [10,12,18,24,27], Rustandi's data for canola oil extraction was the most comprehensive so it was used here. Since the canola and camelina oil extraction processes are so similar, Rustandi's data was used for both canola and camelina. A detailed summary of the input quantities, energy coefficients, emission coefficients, and energy and emission impacts for the vegetable oil extraction stage is given in Table 5a (canola) and b (camelina).

2.2.4. Transportation of vegetable oil to the HDRD plant

Once the vegetable oil has been produced, it must be transported to the HDRD plant. It was assumed for this study that the HDRD plant is located in Redwater, Alberta, and that the vegetable oil is sourced from highly concentrated areas of canola production. Redwater is an industrial area of Alberta with nearby canola production and multiple oil and gas processing facilities. For a 290 million L per year (5000 bbl/day) HDRD plant in Redwater, all of the vegetable oil could be supplied by canola from Census Division (CD) 10 and the round-trip transportation distance for oil from CD 10 to Redwater is approximately 260 km [68]. Since camelina is not a well-established crop in Alberta, the same transportation distance

Table 5
Inputs, energy coefficients, emission coefficients, and impacts for a) Canola oil extraction, base scenario and b) Camelina oil extraction, base scenario.

Operation	Input quantity			Energy coefficients			Emission coefficients			Energy use (MJ/MJ)	Emissions (gCO$_{2e}$/MJ)
	Units	Used value	References	Units	Used value	References	Units	Used value	References		
a) Canola oil extraction, base scenario											
Seed preparation											
Drying heat (from diesel)	MJ process heat/tonne seed	54.5	[12]	MJ/MJ process heat	3.23	[12]	gCO$_{2e}$/MJ process heat	292	[12]	0.009	0.8
Drying electricity	kWh/tonne seed	13.6	[12]	MJ/kWh	9.89	[46]	gCO$_{2e}$/kWh	880	[50]	0.007	0.6
Oil extraction											
Electricity[a]	kWh/tonne seed	40.8[a]	[12]	MJ/kWh	9.89	[46]	gCO$_{2e}$/kWh	880	[50]	0.020	1.8
Steam	kg/tonne seed	369	[12]	MJ process heat/kg	2.00	[12]	gCO$_{2e}$/MJ process heat	126	[12]	0.044	4.7
Cooling water[b]	kg/tonne seed	14,560	[12]	MJ/kg	0.004	[10,67]	gCO$_{2e}$/kg	0.93	calc.	0.003	0.7
Lost solvent (hexane)[c]	L/tonne seed	1.94	[12]	MJ/kg	44.41	[43]	gCO$_{2e}$/kg	17,710	[12]	0.003	1.1
Degumming[d]											
Electricity	kWh/tonne seed	2.2	[12]	MJ/kWh	9.89	[46]	gCO$_{2e}$/kWh	880	[50]	0.001	0.1
Steam	kg/tonne seed	74.3	[12]	MJ process heat/kg	2.00	[12]	gCO$_{2e}$/MJ process heat	126	[12]	0.009	0.9
Process water	kg/tonne seed	8.3	[12]	MJ/kg	0.01	[12]	gCO$_{2e}$/kg	2.47	[12]	0.000	0.0
Oil extraction subtotal										0.09	10.7
b) Camelina oil extraction, base scenario											
Seed preparation											
Drying heat (from diesel)	MJ process heat/tonne seed	54.5	[12]	MJ/MJ process heat	3.23	[12]	gCO$_{2e}$/MJ process heat	292	[12]	0.013	1.2
Drying electricity	kWh/tonne seed	13.6	[12]	MJ/kWh	9.89	[46]	gCO$_{2e}$/kWh	880	[50]	0.010	0.9
Oil extraction											
Electricity[a]	kWh/tonne seed	40.8[a]	[12]	MJ/kWh	9.89	[46]	gCO$_{2e}$/kWh	880	[50]	0.030	2.7
Steam	kg/tonne seed	369	[12]	MJ process heat/kg	2.00	[12]	gCO$_{2e}$/MJ process heat	126	[12]	0.064	3.4
Cooling water[b]	kg/tonne seed	14,560	[12]	MJ/kg	0.004	[10,67]	gCO$_{2e}$/kg	0.93	calc.	0.004	1.0
Lost solvent (hexane)[c]	L/tonne seed	1.94	[12]	MJ/kg	44.41	[43]	gCO$_{2e}$/kg	17,710	[12]	0.004	1.7
Degumming[d]											
Electricity	kWh/tonne seed	2.2	[12]	MJ/kWh	9.89	[46]	gCO$_{2e}$/kWh	880	[50]	0.002	0.1
Steam	kg/tonne seed	74.3	[12]	MJ process heat/kg	2.00	[12]	gCO$_{2e}$/MJ process heat	126	[12]	0.013	1.4
Process water	kg/tonne seed	8.3	[12]	MJ/kg	0.01	[12]	gCO$_{2e}$/kg	2.47	[12]	0.000	0.0
Oil extraction subtotal										**0.14**	**12.3**

[a] Shonnard's estimate was 8.3 kWh/tonne [18].
[b] Emission coefficient calculated based on process water and ratio of energy coefficients.
[c] Emission coefficient based on direct release of hexane to the atmosphere.
[d] Assumed half of Rustandi's input quantity estimates [12] since they were for degumming plus refining.

as canola was assumed for camelina. Super B-train trucks transport the vegetable oil, which have an approximate capacity of 60 m^3, full load fuel consumption of 0.50 L/km [61], and empty-load fuel consumption of 0.31 L/km [61]. The energy and emission coefficients used for vegetable oil transportation were the same as those for seed transportation and like seed transportation, vegetable oil transportation has a very small impact on both energy use (0.002 MJ/MJ for both canola and camelina) and emissions (0.1 gCO$_{2e}$/MJ for both canola and camelina).

2.2.5. HDRD production

Vegetable oil can be converted to HDRD via hydroprocessing, in which triglycerides in the vegetable oil react with hydrogen to produce primarily n-alkanes, as well as propane and CO$_2$ [69]. This reaction takes place in a high-temperature, high-pressure reactor in the presence of a catalyst. Mixing the vegetable oil with a solvent such as hexane prior to the reaction provides numerous benefits including: increased contact between the catalyst and reactants [70,71], reduced formation of undesirable long-chain alkanes [71], and prolonged catalyst life [72]. Once the reaction is complete, the products can be separated using a typical refinery distillation train into four main streams: a light-cut fuel gas stream containing CO$_2$, propane, and some hexane; solvent (hexane) to be recycled to the front-end of the process; a mid-cut HDRD product; a heavy-cut stream containing long-chain alkanes that can be recycled to the front-end of the process [68].

The input quantities for HDRD production in this study were based on previous work done by the authors [68], using an HDRD plant size of 290 million L per year. In the previous work, the authors developed a chemical process model using Aspen Plus® to simulate HDRD production based on experimental work completed by Alberta Agriculture and Rural Development [69]. The model simulated converting canola oil and camelina oil to HDRD at a temperature of 400 °C, pressure of 15.2 MPa g, and used palladium–carbon as a catalyst and hexane as a solvent. Based on the model, the primary inputs for HDRD production include: hydrogen consumed in the hydroprocessing reactions, electricity used to drive pumps and compressors, natural gas used for process heat, cooling water used for process cooling, and hexane makeup (i.e. replacement of hexane lost in the light-cut fuel gas stream). These inputs, along with their corresponding energy coefficients, emission coefficients, and energy and emission impacts are shown in Table 6a and b. For this stage, the inputs and impacts are very similar for canola oil and camelina oil since the product yields from hydroprocessing are similar for both oils.

Note that the emission coefficient used for hexane in this stage of the LCA is much lower than the emission coefficient used for

Table 6
Inputs, energy coefficients, emission coefficients, and impacts for converting a) Canola oil to HDRD, base scenario and b) Camelina oil to HDRD, base scenario.

Operation	Input quantity			Energy coefficients			Emission coefficients			Energy use (MJ/MJ)	Emissions (gCO_{2e}/MJ)
	Units	Used value	References	Units	Used value	References	Units	Used value	References		
a) Canola oil to HDRD, base scenario											
Hydroprocessing & distillation											
Hydrogen consumption	kg/L HDRD	0.02	[68]	MJ/kg	217	[73]	gCO_{2e}/kg	11,888	[73]	0.078	4.3
Electricity	kWh/L HDRD	0.08	[68]	MJ/kWh	9.89	[46]	gCO_{2e}/kWh	880	[50]	0.018	1.6
Natural gas	MJ/L HDRD	5.35	[68]	–	–	–	gCO_{2e}/MJ	56.58	[43]	0.118	6.7
Cooling water[a]	m^3/L HDRD	0.07	[68]	MJ/kg	0.004	[10,67]	gCO_{2e}/kg	0.93	Calc.	0.006	1.5
Hexane makeup[b]	kg/L HDRD	0.22	[68]	MJ/kg	44.41	[43]	gCO_{2e}/kg	3070	Calc.	0.216	15.0
Oil extraction subtotal										**0.44**	**29.0**
b) Camelina oil to HDRD, base scenario											
Hydroprocessing & distillation											
Hydrogen consumption	kg/L HDRD	0.02	[68]	MJ/kg	217	[73]	gCO_{2e}/kg	11,888	[73]	0.081	4.4
Electricity	kWh/L HDRD	0.09	[68]	MJ/kWh	9.89	[46]	gCO_{2e}/kWh	880	[50]	0.019	1.7
Natural gas	MJ/L HDRD	5.53	[68]	–	–	–	gCO_{2e}/MJ	56.58	[43]	0.122	6.9
Cooling water[a]	m^3/L HDRD	0.07	[68]	MJ/kg	0.004	[10,67]	gCO_{2e}/kg	0.93	Calc.	0.006	1.5
Hexane makeup[b]	kg/L HDRD	0.21	[68]	MJ/kg	44.41	[43]	gCO_{2e}/kg	3070	Calc.	0.205	14.2
Oil extraction subtotal										**0.43**	**28.7**

[a] Emission coefficient calculated based on process water (from oil extraction stage) and ratio of energy coefficients.
[b] Emission coefficient calculated based on molecular weight and number of carbon atoms, see Ref. [74].

hexane in the oil extraction stage. In the oil extraction stage, hexane is directly released to the environment whereas in the HDRD production stage, the lost hexane would be burned with the light-cut fuel gas stream; when hexane is directly released to the environment, it has a higher global warming potential than when it is combusted directly [74]. However, the total mass of hexane lost in each stage must also be considered. It will be shown in the Results and discussion that despite a lower emission coefficient for hexane loss in the HDRD production stage, the overall GHG impact of hexane loss is much greater during HDRD production than during oil extraction.

2.2.6. Transportation of HDRD to the consumer

In the Province of Alberta from 2006 to 2010, the amount of diesel fuel sold has averaged approximately 3.5 billion L per year [75]. Therefore, a 290 million L per year HDRD plant would satisfy approximately eight percent of the diesel demand in Alberta. Although this supply is greater than the two percent renewable fuels standard recently established in Alberta, it is assumed that all of the HDRD produced at the plant is consumed in the two major cities of Alberta: Edmonton and Calgary. Edmonton is located approximately 65 km south of Redwater and Calgary is located approximately 380 km south of Redwater. If half of the HDRD produced is consumed in Edmonton and half in Calgary, the average round-trip transportation distance from Redwater to the consumer is 445 km and this distance was used in the LCA.

It was assumed that super B-train trucks transport the HDRD to the consumer. These are the same trucks used for the vegetable oil transportation stage, so the same capacity, fuel consumption rates, energy coefficients, and emission coefficients mentioned earlier also apply for HDRD transportation. As was the case for other transportation stages, the impacts on energy use (0.003 MJ/MJ for canola and camelina) and emissions (0.2 gCO_{2e}/MJ for canola and camelina) are very small for HDRD transportation.

3. Results and discussion

3.1. Base scenario

In the base scenario, energy and emissions were allocated between the HDRD, propane fuel gas stream, and oilseed meal on a mass basis. Fig. 2a and b illustrate the energy and emission inputs for each stage of the LCA, along with allocations to each product for canola HDRD and camelina HDRD production respectively. For the base scenario, canola HDRD generates 48 gCO_{2e}/MJ with an NER of 1.7 (inverse of energy use) and camelina HDRD generates only 38 gCO_{2e}/MJ with an NER of 2.0. Camelina HDRD's superior emission and energy performance is mostly due to lower fertilizer use, lower soil N_2O emissions, and higher yield compared to canola.

From Fig. 2a and b, it is clear that the field stage generates the most emissions, followed by the HDRD production stage, the oil extraction stage, and the transportation stages. In the field stage, the greatest contributors to emissions are fertilizer use and soil N_2O emissions whereas in the HDRD production stage, hexane makeup contributes the most to emissions; in the experiments used as a basis for this study [69], a relatively high solvent to vegetable oil ratio of 7:1 was used but in a real HDRD plant, the solvent to vegetable oil ratio and corresponding hexane makeup rate would likely be lower, resulting in lower emissions than what is shown here. For the oil extraction stage, electricity and steam use generate the most emissions and for all of the transportation stages, the emissions are essentially negligible compared to the other stages.

The relative breakdown of energy use is essentially the same as the breakdown already discussed for emissions. However, unlike the emissions breakdown, the HDRD production stage is slightly more energy intensive than the field stage for camelina HDRD. This phenomenon only occurs for camelina HDRD because camelina uses less N fertilizer than canola and the input quantity of N fertilizer was used to calculate soil N_2O emissions, which impact total emissions but not energy use. Similar to the emissions breakdown, hexane makeup in the HDRD production stage adds greatly to energy use, so reducing the hexane makeup rate in a real HDRD plant would result a better NER.

In the co-product allocation, HDRD receives the greatest allocation of emissions and energy use, followed by the oilseed meal, and the propane fuel gas stream. Due to the lower oil content of camelina compared to canola (30% vs. 44%), a higher share of emissions and energy use were allocated to camelina meal compared to canola meal. As discussed in Section 2.2.3, estimates of camelina seed oil content in literature vary significantly.

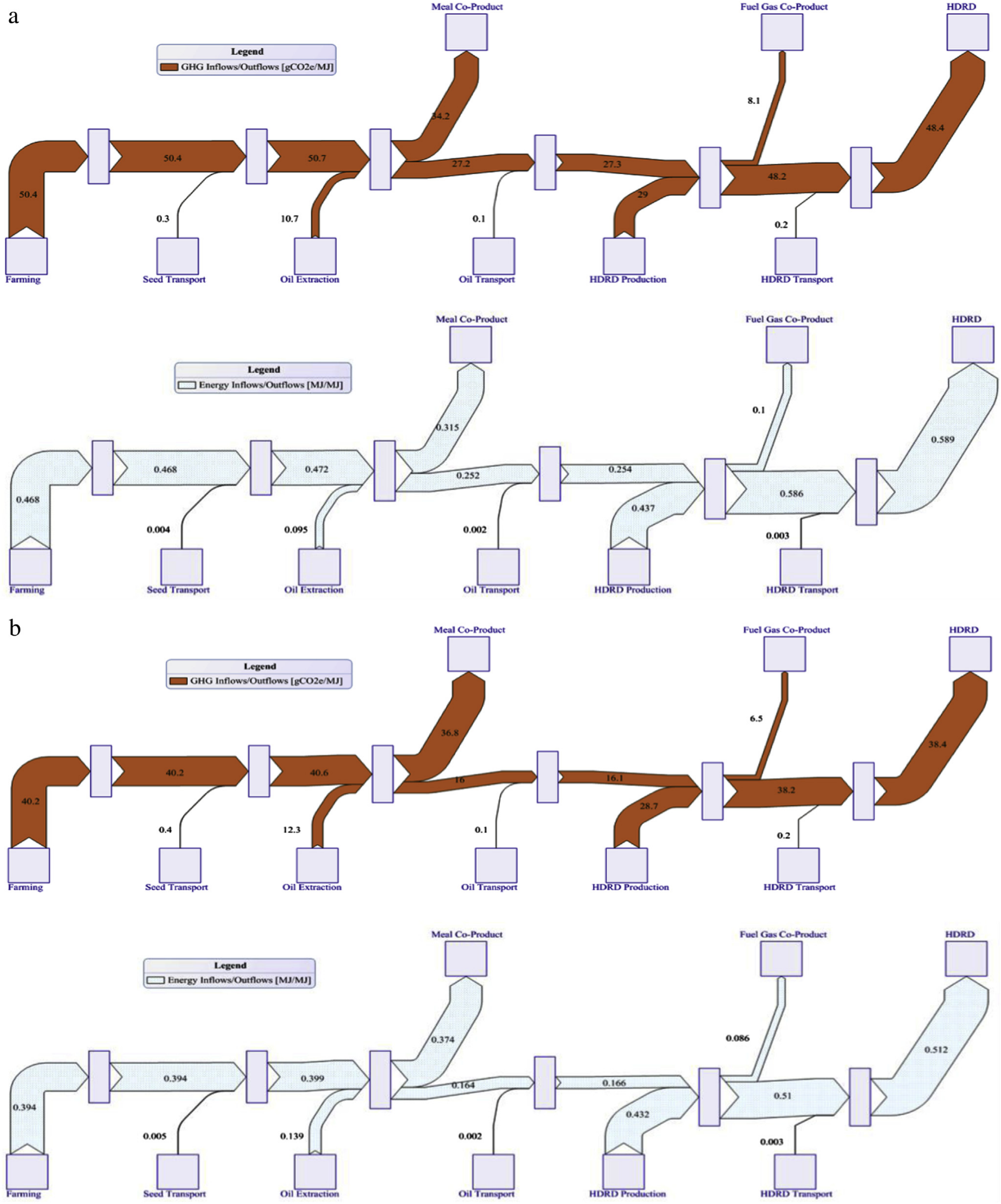

Fig. 2. Energy and emission inflows/outflows for a) Canola-HDRD and b) Camelina-HDRD.

However, increasing the oil content of camelina to 38% [66] in the LCA model has essentially no impact on the emissions and NER of camelina HDRD; a higher oil content results in lower total emissions and energy use in the oil extraction stage but a greater share of the total emissions and energy use are allocated to the oil and subsequent HDRD. This dynamic between the oil content and allocation results in a balance, but only for the mass allocation method.

3.2. Other scenarios – sensitivity analysis

As shown in Table 1, many scenarios were analyzed in this study to account for differences in variables (i.e. yield and field N_2O emissions) and methodological assumptions (i.e. co-products, allocation methods, and land-use changes) that could significantly impact the LCA results. The life cycle GHGs and NER for HDRD for each scenario are shown in Figs. 3 and 4 respectively. Note that in Fig. 4, scenarios 3–8 were not included because the NERs for those scenarios are the same as the base scenario NER.

Some key observations from Figs. 3 and 4 are:

- Including straw in the allocation (scenario 1) significantly reduces the emissions and energy-use allocated to HDRD compared to the base scenario. This reduction occurs because of the high emission and energy intensity of the field stage, coupled with high straw to seed ratios for canola and camelina – 4.1 kg/kg for canola [76] and 4.0 kg/kg for camelina [77].
- Changing the allocation method from mass to economic value (scenario 2) increases HDRD emissions by nearly 50% and decreases NER by 30%. Recent canola meal prices in Western Canada were much lower on a mass basis than diesel prices – \$0.22/kg [78] vs. \$1.35/kg [79] – so for scenario 2 most of the energy and emission burdens go to the HDRD. Since camelina meal price data was not readily available, it was assumed that camelina meal sold for the same price as canola meal.
- Increasing the soil N_2O emission factor from 0.76% to 5% (scenarios 3–7), increases the GHGs allocated to HDRD linearly by up to 75% for canola HDRD and 53% for camelina HDRD. Camelina HDRD is less sensitive to changes in the soil N_2O emission factor because less nitrogen fertilizer is used to grow camelina.
- Including land-use changes (scenario 8) nearly doubles the GHGs allocated to canola HDRD but has no impact on camelina HDRD since camelina could replace the fallow stage in crop rotation.
- Changing the oilseed yield from average to minimum (scenario 9) or to maximum (scenario 10) only changes the GHG allocations by a maximum of 15% and the NERs by a maximum of 11%.
- Removing camelina meal from the co-product allocations has a great impact on the GHGs and NER for camelina HDRD. Under mass allocation (scenario 11), GHGs increase by 84% and NER decreases by 39% compared to the base scenario. Under economic value allocation (scenario 12), GHGs increase by 116% and NER decreases by 48%.
- None of the scenarios resulted in an NER less than 1, meaning that in all scenarios, the return on fossil energy invested was positive.

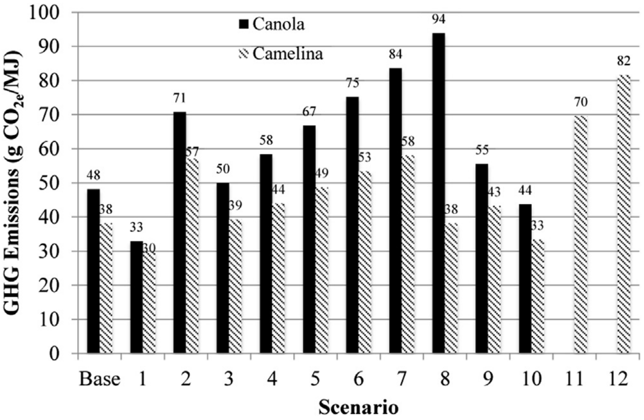

Fig. 3. Life cycle GHGs for HDRD for the scenarios analyzed.

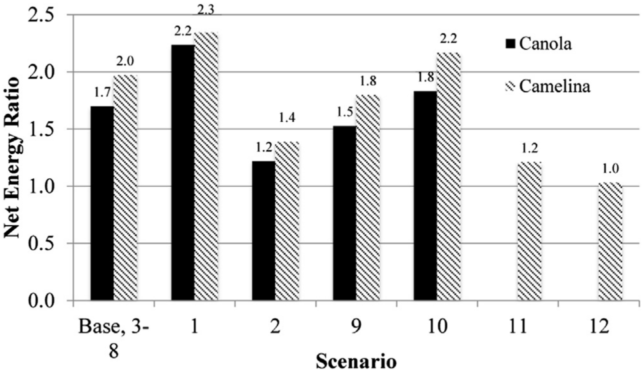

Fig. 4. NER for HDRD for the scenarios analyzed.

In all direct comparison scenarios, camelina HDRD outperforms canola HDRD in terms of GHGs and NER. However, if camelina meal cannot be sold (scenarios 11 and 12), canola HDRD outperforms camelina HDRD. Camelina meal is currently accepted as animal feed on a very limited basis, so at this point in time, canola HDRD is more sustainable than camelina HDRD based on GHGs and NER. If camelina meal gains greater acceptance as animal feed in the future, camelina will likely be a much better choice from an environmental perspective than canola for renewable fuels production.

3.3. Comparison with literature

Few LCA studies are available in literature for canola and camelina HDRD, but the results in those studies agree reasonably well with the base scenario results in this study. Arvidsson [17] estimated the life cycle GHGs and NER of rapeseed HDRD at approximately 67 gCO_{2e}/MJ and 2.4 respectively. The higher GHGs in that study can be partially explained by Arvidsson's use of a higher emission factor for soil N_2O emissions (1.25% vs. 0.76%). Other differences in emissions and NER are likely due to differences between studies in farming location (Germany vs. Western Canada), allocation method (displacement vs. mass), and energy and emission coefficients.

Shonnard and Williams [18] used mass allocation, energy allocation, and displacement allocation to estimate the life cycle GHGs and NER of camelina HDRD. In that study, the life cycle GHGs were found to be approximately 16 gCO_{2e}/MJ (mass allocation), 18 gCO_{2e}/MJ (energy allocation), or 4 gCO_{2e}/MJ (displacement allocation). Specific NER data was not given for each allocation type, but the general NER given for camelina HDRD was approximately 4.0. Shonnard's study suggests much lower energy and emission intensities for camelina HDRD than this study, which is likely due to several differences in assumptions. Shonnard's study was based in the United States and used lower fertilizer inputs for the farming stage and lower energy inputs for the oil extraction and HDRD production stages. Since camelina is not widely grown in Canada or the US, the fertilizer inputs are not yet well defined so both studies' estimates may be valid. For the HDRD production stage, Shonnard used data from UOP's commercial HDRD process, so Shonnard's estimates for that stage may be more accurate than this study's, which were based on experimental data and chemical process modeling.

3.4. Comparison with diesel and biodiesel

Compared to fossil diesel, HDRD from canola or camelina appears to be a more sustainable choice. Estimates in literature for the GHGs and NER for fossil diesel vary from approximately 86–

94 gCO_{2e}/MJ and 0.79–0.85 MJ/MJ respectively [14,24]. Therefore, in the base scenario, canola HDRD offers a reduction in GHGs of approximately 47% and more than twice the NER compared to fossil diesel; camelina HDRD is even better, with a 58% reduction in GHGs and 2.4 times the NER of fossil diesel. None of the extra scenarios showed that HDRD has an NER less than fossil diesel and only scenarios 7 (canola, 5% N_2O emission factor), 8 (canola, LUC included), and 12 (camelina, meal excluded, economic-value allocation) showed that GHGs from HDRD could fall into the same range as GHGs from fossil diesel.

Many LCAs have been completed on biodiesel from canola/rapeseed [9–13,24] but LCAs are limited for biodiesel from camelina [24]. The estimates of GHGs and NER in these studies vary widely, but average at approximately 50 gCO_{2e}/MJ and 2.8 MJ/MJ for canola-biodiesel, and 29 gCO_{2e}/MJ and 2.4 for camelina-biodiesel. These emission levels are very similar to the emission levels found in this study for canola HDRD and camelina HDRD. However, the NERs in literature for canola and camelina biodiesel are generally slightly higher than those found in this study for HDRD.

4. Conclusion

In this study, data-intensive life cycle assessment models were developed to estimate the NER and GHGs for HDRD produced from canola oil and camelina oil in the Province of Alberta, Canada. By building custom LCA models, the authors were able to validate the data sources and calculation methods used in the analysis, and create excellent model flexibility and transparency. If camelina meal can be directly substituted for canola meal as animal feed, camelina-based HDRD is environmentally superior to canola-based HDRD due to lower agricultural inputs and higher yields for camelina. However, since there is currently little market demand for camelina meal, it is unrealistic to consider it as a co-product, making canola-HDRD a more environmentally friendly option at this time. A sensitivity analysis determined that the choice of allocation method, co-products, soil N_2O emission factor, and whether to include LUC could significantly impact the LCA results. However, even in the most extreme scenarios, both canola-HDRD and camelina-HDRD appear to be more sustainable than fossil diesel due to lower GHGs and higher NERs. Based on the available literature, GHGs for HDRD production are similar to those for biodiesel, while the NER for HDRD appears slightly lower than the NER for biodiesel.

In producing HDRD, the farming stage and the oil conversion stage (i.e. the HDRD production stage) are the most energy and emission intensive. To improve the sustainability of HDRD, researchers and industry could focus on minimizing nitrogen fertilizer use in farming (while maintaining yield) and optimizing solvent use during hydroprocessing. For camelina specifically, more research is needed to evaluate the viability of camelina meal as animal feed in order to justify including it as a co-product in energy and emission allocations.

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