LIFE CYCLE ANALYSIS OF CAMELINA BIODIESEL AND JET FUEL

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Namrata Dangol

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Major Professor: Dev S Shrestha, Ph.D., P.E.

AUTHORIZATION TO SUBMIT THESIS

This thesis of Namrata Dangol, submitted for the degree of Master of Science with a Major in Biological and Agricultural Engineering and titled “Life Cycle Analysis of Camelina Biodiesel and Jet Fuel”, has been reviewed in final form. Permission, as indicated by the signatures and date given below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: …………………………………………. Date: ………………………...
Dev S. Shrestha

Committee
Members: ………………………………………….. Date: ………………………...
Jon Van Gerpen

………………………………………….. Date: …………………….....
Jack Brown

Department
Administrator: …………………………………………... Date: ………………………..
Thomas Hess

Discipline’s College
Dean: ………………………………………… Date: ………………………..
Larry Stauffer

Final Approval and Acceptance:

Dean of the College
of Graduate Studies: …………………………………………… Date: ……………………….
Jie Chen, Ph.D.

ABSTRACT

Camelina sativa (Camelina) could be a potential feedstock to help meet the goal of 36 billion gallons of biofuel production in the United States by 2022, as set forth by EISA of 2007. This research is focused on assessing the energy balance and greenhouse gas (GHG) emissions from camelina biodiesel grown and produced in the Pacific Northwest (PNW) region of the USA. Data were collected from a camelina farm in the region and compared to literature values. Energy used in camelina crushing and transesterification were measured at the University of Idaho. Life cycle analysis showed that use of camelina biodiesel reduces GHG emissions by 72% compared to 2005 baseline diesel fuel. Camelina biodiesel at B100 level, however, did not meet the ASTM D6751 specification for oxidative stability without any additives but could be corrected with proper additive. Camelina had a smaller seed size compared to canola and consequently required 23% more energy for crushing. Despite higher energy use for crushing, the net energy ratio for camelina biodiesel was found to be 3.68.

From the agronomic standpoint, camelina can be incorporated as a rotational crop into low rainfall areas of the PNW. Wheat areas of PNW with annual rainfall from 19 to 38 cm (7.5-15") and currently incorporating fallow into their rotations were considered as potential areas for camelina. There were 846,500 hectares (2.1 million acres) of land available in the region that could potentially produce 443.0 million L of biodiesel (117.1 million gal) and 1.2 billion kg of meal per year. This meal quantity is about 12.1% of the potential camelina meal that could be used as livestock feed in the PNW. Therefore, it was concluded that the meal has adequate market to be consumed locally as livestock feed.

This research also conducted the life cycle analysis of camelina jet fuel produced in the laboratory scale facility. The jet fuel was produced via deoxygenation of the camelina oil in an inert environment, in the presence of Pd/Al_2O_3 catalyst. The jet fuel fraction was separated with fractional distillation. The produced jet fuel was tested for ASTM D-7566-13 specifications for aviation fuel. The produced jet fuel did not meet the specifications for freezing point by 2°C at its neat form with no additives. The energy balance and GHG emission analysis of the produced fuel was performed. The NER of the fuel was found to be 1.36, and the GHG emission reduction was 57% compared to the conventional jet fuel.

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CHAPTER 1: INTRODUCTION

CAMELINA

Camelina (*Camelina sativa*), is a Brassicaceae family oilseed crop similar to mustard, canola, and rapeseed (USDA, 2013). Camelina is a relatively new crop to the USA that was originally brought from central Europe. It is currently being grown on approximately 50,000 acres of land in the U.S., primarily in Montana, Eastern Washington, and the Dakotas (Johnson and McCormick, 2010). Camelina is a short-season crop (85-100 days) generally grown as an early summer annual oilseed crop but can be grown as a winter annual in milder climates (Hunter and Roth, 2010). It germinates at as low as 12°F (Ehrensing and Guy, 2008), and seedlings are very frost tolerant (Hulbert et al., 2012). Camelina is more tolerant under drought conditions and may be better suited to low rainfall regions than other oilseed crops (Mcvay and Lamb, 2004; McVay and Khan, 2011).

Camelina could be a potential rotational crop in wheat cropland, due to its low rainfall requirement and short growing season. The reported oil content of the seed is 30-40% (USDA-NRCS, 2011). The oil from camelina can be used to make biodiesel, renewable diesel or bio jet fuel as a renewable fuel. If a renewable fuel reduces greenhouse gas (GHG) emissions by at least 50%, the fuel qualifies to be an “advanced biofuel” (US-EPA, 2010), allowing the producer to receive tax incentive or through generation of Renewable Identification Numbers (RINs) according to the Renewable Fuel Standard (RFS2) program. Ensuring that biofuel meet the EPA’s renewable fuel requirements will play a major role in determining the success of a renewable fuel industry. After initial life cycle analysis, USEPA has approved the renewable fuel pathways for camelina in 2013 stating that camelina biodiesel pathway is similar to soybean based biofuel (USEPA, 2013). The report did not quantify the GHG reduction from use of camelina biofuel. This research specifically looks into production pathways for camelina biofuel and quantifies the GHG emission reduction from the use of camelina based biodiesel and bio jet fuel.

LIFE CYCLE ANALYSIS (LCA)

Life cycle analysis is a technique used to quantify energy and environmental impacts of a product. It is a “cradle to grave” approach for assessing industrial system, which begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth (Guinee, 2002). LCA evaluates all stages of a product's life cycle to estimate the cumulative environmental impact. It provides a comprehensive view of the environmental aspects of the products or process and an accurate picture of the true environmental tradeoffs in products and process selection (NRMRL-USEPA, 2006). The information can help users, producers, public, and policy makers identify a product that results in the least burden to the environment (Pradhan, 2010).

LCA compiles an inventory of relevant energy and material inputs and environmental releases, evaluating the environmental impacts associated with identified inputs and releases (Figure 1.1). The inputs include materials and non material such as electrical energy and output includes direct emissions, emissions from co-product use and the waste stream.

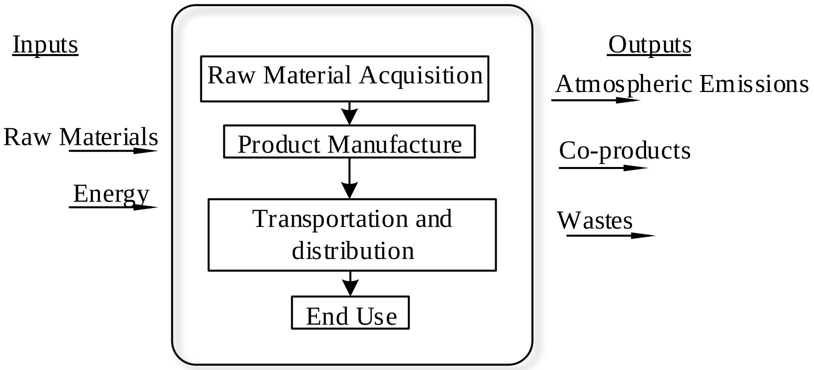

Figure 1.1: Stages of life cycle (NRMRL-USEPA, 2006)

Energy balance is a branch of LCA which accounts for energy inputs and outputs in making a biofuel. One measure of energy input and output is the net energy ratio (NER), expressed as:

$$NER = \frac{Biofuel\ Energy\ Output}{Biofuel\ Share\ of\ Total\ Energy\ Input} \qquad 1.1$$

Another measure of energy is the fossil energy ratio (FER) which is used as the measure of the renewability of the biofuel. It is defined as the ratio of the energy output from the final biofuel to the fossil energy required to produce the biofuel(Spath and Mann, 2001). If all of the fuel used is non-renewable, then FER is equal to the NER.

$$FER = \frac{Biofuel\ Energy\ Output}{Biofuel\ Share\ of\ Fossil\ Energy\ Input} \qquad 1.2$$

Life cycle greenhouse gas (GHG) emissions accounts for the GHGs emissions during all stages of fuel production from raw material production to final use (Pradhan, 2010).

OBJECTIVES OF THE STUDY

This research is focused on life cycle analysis both in terms of GHG emissions and energy performance of camelina biodiesel and bio jet fuel produced in a small scale plant. This research also estimates camelina production potential in the Pacific Northwest region as a rotational crop in wheat - fallow rotations. Finally, this research looks in the comparative cost of bio jet fuel and biodiesel production from camelina.

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CHAPTER 2: PRODUCTION POTENTIAL AND LIFE CYCLE ANALYSIS OF CAMELINA BIODIESEL IN THE PACIFIC NORTHWEST

INTRODUCTION

Camelina *(Camelina sativa)*, is an oilseed crop from the Brassicaceae family (USDA, 2013) similar to mustard, canola, and rapeseed. It is a relatively new crop in the USA, and currently being grown on approximately 50,000 acres of land primarily in Montana, Eastern Washington, and the Dakotas (USEPA, 2013; Pilgeram et al., 2007). Agronomic trials are being conducted for camelina in the states of Nebraska, South Dakota, Wyoming, Colorado, Kansas, and Minnesota in the USA (Pavlista and Baltensperger, 2007; Gesch and Cermak, 2011) and western Canada (Gugel and Falk, 2006) to better understand the crop behavior. Camelina can be used to make biodiesel as a renewable fuel. Camelina could be a potential biodiesel feedstock crop due to its low moisture tolerance, short growing season (85–100 days) and relatively high oil content (30-40%) (Pavlista et al., 2011; Pilgeram et al., 2007).

According to the Energy Independence Act (EISA) of 2007, a biofuel qualifies as an “advanced biofuel” if the fuel reduces greenhouse gases (GHG) emissions by at least 50% compared to baseline petroleum fuel. It allows the producer to receive higher monetary incentives through tax credits or through generation of Renewable Identification Numbers (RINs) as the per Renewable Fuel Standard (RFS2) program. However, the Federal tax credit on the biodiesel/biodiesel mixture has expired on Dec. 31, 2013, which could be reauthorized by Congress. In 2013, USEPA identified the fuel pathways for biofuels produced from camelina oil, and stated that it could qualify as an advanced biofuel (USEPA, 2013). This paper quantifies the actual GHG reduction percentages for camelina biodiesel which were not specifically determined in the EPA study. Ensuring that biofuels meet the EPA’s renewable fuel requirements will play a major role in determining the financial success of a renewable fuel industry. Relative costs of renewable fuel compared to petroleum fuel vary. In the short term, the price depends on market dynamics, subsidies, inflation and crude oil price. However, one good indicator of how biofuel price would compare in the future is its net energy ratio (NER). NER is the ratio of energy output from biofuel per unit of total energy used to produce the fuel. The fuels used in production of biofuel system are mainly diesel, gasoline, natural gas and electricity and their relative price shifts in tandem (Pradhan et al., 2011). NER can be used to compare the production efficiency of a biofuel to a petroleum fuel. For instance, petroleum diesel uses 0.13 units of energy for every unit of energy mined (Sheehan et al., 1998). This causes the NER for petroleum diesel to be 0.87/0.13 (≈ 6.7). Current NER for soybean biodiesel is 5.54 (Pradhan et al., 2011). This indicates that if fuel prices for biodiesel and petroleum diesel were in proportion, than soybean biodiesel would be more costly and less profitable than petroleum diesel production. The situation, however, may change if the future mining of petroleum becomes more energy intensive.

Life cycle analysis (LCA) evaluates the performance of a biofuel, relative to its petroleum fuel counterpart, in regards to GHG emission reductions and energy balance. The fossil energy ratio (FER) measures the renewability a biofuel. FER is the ratio of energy output from the biofuel per unit of fossil energy input. The FER calculation does not include energy input from renewable sources, such as hydropower or solar. Higher FER value corresponds to higher renewability of the fuel, but it does not ensure its economic viability (Pradhan et al., 2008). This study is focused on computing NER, FER and GHG emission of the camelina biodiesel.

Being relatively new, camelina does not have as established a market-base as other oilseeds such as soybean and canola. In July 2011, USDA announced that the Biomass Crop Assistance Program (BCAP) would make grants available for expanding camelina production in Montana, California, Oregon and Washington (USDA-FSA, 2011). However, yield, price risk concerns, inadequate market and lack of production information were the reasons that deterred farmer participation (Young et al., 2012). Canola is a close competitor of camelina as a rotational crop and has a higher return on investment compared to camelina in higher rainfall regions (Young et al., 2012). Wheat is the primary crop grown in the Pacific Northwest (PNW) and has a higher return on investment than any rotational crops (UI, 2012). Peas, lentil, or canola is rotated with wheat to break wheat monoculture once every 3-4 year in higher rainfall regions (>38 cm). However, in lower rainfall regions (≤ 38 cm), the land is left fallow (Schillinger et al., 2010). Camelina can be grown in some of these fallow areas because of its relatively short growing period and low moisture tolerance (Shonnard et al., 2010). This study estimated the production potential of camelina as a rotational crop in low rainfall areas of the PNW.

Because of its relatively higher oil content, camelina is cold pressed using screw presses. Cold pressed camelina meal contains 10–14% oil by weight which potentially can be extracted using a solvent extraction method. Solvent extraction, however, is usually not performed on the cold pressed meal as the scale is inadequate to justify the cost. Interview with farmers also revealed that the high oil content meal has a higher demand for animal feed so further reducing the need for hexane extraction. Therefore, the meal after cold press is sold as it is. Camelina meal is better suited than rapeseed or mustard for animal feed because of lower glucosinolate levels of 14.5 - 36.2 mmol/kg (Schuster and Friedt, 1998; Berhow et al., 2013) compared to 100-120 mmol/kg in rapeseed and 62.4-77.1 mmol/kg in mustard (Matthäus and Luftmann, 2000). Canola, however, has a comparable or slightly lower glucosinolate level of 5-20 mmol/kg. Lower glucosinolate makes a meal suitable as a livestock feed mix (Pilgeram et al., 2007) and as a result, camelina meal has been approved as a feed mix (ingredient) by the FDA up to 10% in poultry and beef cattle, and 2% in swine (MDA, 2012; EFSA, 2008). This study also estimated the production potential of camelina meal, and its market in local livestock industry.

METHODOLOGY

LCA System Boundary

This LCA covers the following stages of fuel production i) camelina production ii) camelina transportation from farm to crushing plant iii) biodiesel production from camelina oil, and iv) biodiesel transportation and distribution. All materials and energies invested during the operation and processing during these stages were included. Equivalent life cycle energy, which is embedded energy plus the energy used in mining, processing, transportation and distribution of a material, was used in the energy analysis.

This LCA is based on data from a camelina farm and biodiesel plant located in La Crosse, WA. The farmer has been growing dry-land winter camelina (non-irrigated) on 60-120 ha of land for the last 4 years (since 2009) as a rotational crop. Annual rainfall during that period was 30-36 cm, and annual average temperature was -1 to 10 °C. Seeding is done in late October (direct seeding followed by harrowing) and harvested in late March through early April with a combine (same as canola combine). The farmer produced biodiesel from the camelina oil crushed in his oil press, near the seed storage area. The produced biodiesel is used as fuel for his farm operations. Seed transportation consists of hauling the harvest from the field to the storage area and to crushing facility which was within five mile radius. This may not be the case for other farmers. Since transportation distance to the crusher may vary by farm, a sensitivity analysis showing the impact of hauling distance on overall LCA was included later in this paper. Likewise, the effect on the LCA resulting from relatively highly variable inputs such as oil transportation was also included as sensitivity analysis. Given that camelina is incorporated as a rotational crop and does not compete for land resource, indirect land use changes were not included in this study.

Data Collection

The data for camelina feedstock production was obtained from the farmer. Energy input for camelina crushing and biodiesel production was measured experimentally at the University of Idaho Biodiesel lab. A screw press type oil expeller (S-52 model, Hander Oil Machinery, Osaka, Japan) run by a 2.95 kW (4 hp) 3-phase induction motor was used for crushing. The press has a 3 stage 1 kW silicone blanket heated seed auger with an insulated jacket. The press can crush up to 50 kg/h (110 lb/h). The meal after crushing is augured to a bin using a fractional horse power motor. The seed was preheated to 40 °C using the seed heater before crushing. The energy used for the motor, heater and augur were recorded separately using a 3-phase power data logger (Extech model 382090, Nashua, NH).

The oil content was estimated following the procedure outlined by Hammond (1991) using a Newport MKIIIA Nuclear Magnetic Resonance (NMR) Analyzer (Oxford Instruments Inc, Concord, MA). The NMR was calibrated with a single reference sample of known oil content and the sample analysis carried out as described by Howard and Daun (1991).The procedure is based on ISO 5511-1984. The fatty acid content of the oil was determined using gas chromatography as described by Hammond (1991). The moisture content of the seeds was measured by the oven drying method as per ASABE S352.2 FEB03 (ASABE, 2012).

Seed Size Analysis

Assuming ellipsoidal seed geometry of camelina seeds with hull thickness ‘t’ and seed radii ‘a’ , ‘b’ and ‘c’ in principal axes, the meal to total volume ratio (M) is given by:

$$M = \frac{(a-t)(b-t)(c-t)}{abc} \qquad 2.1$$

The equation shows that for the same hull thickness, the ratio of meal increases non-linearly with the seed radii and asymptotically reaches unity when the seed thickness is negligible compared to seed radius. Since the hull has almost no lipid or protein, a larger seed such as canola would have more overall oil percentage even though the meal and protein percentage is the same in the cotyledon. In addition to smaller meal to total volume ratio, smaller seeds also require more energy to break open. Assuming equal hull tensile strengths, and taking the approximate value of the ellipse circumference as$2\pi\sqrt{\frac{a^2+b^2}{2}}$, the ratio of internal stress required to rupture the outer hull can be expressed as:

$$\frac{P_1}{P_2} \approx \frac{a_2 b_2\sqrt{a_1^2+b_1^2}}{a_1 b_1\sqrt{a_2^2+b_2^2}} \times \frac{t_1}{t_2} \qquad 2.2$$

where subscript 1 and 2 indicates radii and thicknesses of two different seed sizes. For the same hull thickness, and similar ellipsoid ($\frac{a_1}{b_1} = \frac{a_2}{b_2}$) , the pressure ratio can be simplified to$\frac{P_1}{P_2} = \frac{a_2}{a_1} = \frac{b_2}{b_1}$. The equation shows that crushing pressure required is inversely proportional to the seed size; that is higher pressure is required to crush a smaller seeds with same hull thickness than a larger seeds. Higher pressure translates to more frictional loss and consequently more energy of crushing per unit volume of seed.

To verify the effect of seed size on energy requirement, camelina seed size and hull thickness were measured from a seed tomogram taken from an Omax G012001998 optical microscope (Omax Corporation, South Kent, WA) at 10x magnification (Figure 2.1). The seed sizes were measured using sieve analysis as per ANSI/ASAE S319.3 FEB03 (ASABE, 2003). The comparison of seed size was made between relatively larger canola seed to camelina seed. The theoretical meal to total seed volume was compared to measured values for both seeds. The mass of the seed meal to total seed mass was also measured using an electronic measuring scale.

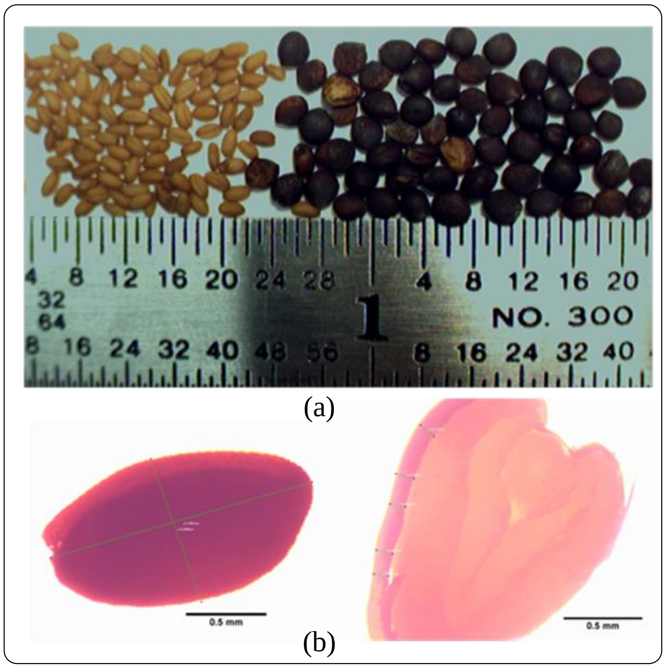

Figure 2.1: Seed comparison left: Camelina, right: Canola a) Image with ruler lines at 1/32 inches b) Hull thickness was measured using seed tomogram microscopy

Biodiesel was produced in a six gallon capacity stainless steel drum reactor (Electro-Flex Heat Inc., Bloomfield, CT) using 100% excess methanol to complete the reaction and using sodium methoxide as catalyst. The reactor had 250W (1/3 hp) stirrer and 1000 W silicone belt heater. The excess methanol from glycerol after separation was recovered using a Rotavapor (Buchi, R-114, Switzerland). The produced biodiesel was tested for flash point, water content, kinematic viscosity, acid number, oxidative stability, distillation temperature, sulfur content, and cloud point according ASTM D6751 specifications. Cetane number was estimated from the fatty acid ester composition of the biodiesel using an empirical equation (Ramírez-Verduzco et al., 2012).

The energy input in transportation and distribution of feedstock and biodiesel were obtained from Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) model (ANL, 2012).

Soil Emissions

The soil emissions from camelina cultivation were obtained from LCA model GHGenius v4.03 ((S&T)^2 Consultants Inc., 2013a), modeled for Western US regions from USDA data. The model takes into account the direct and indirect emissions, as well as the carbon sequestration in the soil. The direct emission includes N_2O

emission related to added nitrogen fertilizer, crop biomass added to the soil, nitrogen present in the soil, and due to soil carbon changes. The emissions of CO_2 and CH_4 related to nitrogen emission were also included as direct emission in the model. The N_2O emission from nitrogen volatilization, leaching and runoff were regarded as indirect emissions as escaped nitrogen converts to N_2O offsite. The carbon sequestered in the soil was also calculated and subtracted from the soil emissions to get the net soil emissions. The methodology is described in detail in GHGenius Model 4.03 Volume 1 and 2. ((S&T)^2 Consultants Inc., 2013b; (S&T)^2 Consultants Inc., 2013c)

Energy Conversion Factors and Co-Product Energy Allocation

The materials used in the inventory list were converted to their equivalent life cycle energy contents. The life cycle energy for an input is defined as the total of the embedded energy, and the energy expended during extraction, processing, transportation, and distribution. The embedded energy for fuel inputs like diesel, gasoline and natural gas were taken as their lower heating value, and for all other inputs their higher heating values were taken. This method is consistent with previous studies such as Pradhan et al. (2011). The life cycle energy of electricity was based on the weighted average for the PNW region. The energy used in the process needs allocation among coproducts. Coproducts in this case are camelina meal, biodiesel and crude glycerin. A mass-based co-product allocation method was used and provides reasonable and reproducible results (Vigon et al., 1993; Pradhan et al., 2008).

Camelina Potential in PNW as a Rotational Crop with Wheat

The economic breakeven yield for non-irrigated camelina was estimated to be 980 kg/ha (875 lbs/acre) at the price of \$0.40/kg (Painter, 2011). An estimation using Hergert et al. (2011) showed a minimum of 19 cm (7.5 inch) of rainfall equivalent is required to obtain this breakeven yield. Taking the common crop rotation pattern within the viable rainfall zone (19-38cm), potential camelina areas were identified using ArcGIS 10 software. The common three and four year crop rotations were winter wheat-winter wheat-fallow (WWF) and winter wheat-winter wheat-fallow-spring wheat (WWFS), respectively (Figure 2.2). The crop coverage data between year 2008 and 2012 from USDA (USDA-NRCS, 2012), were used to identify crop rotation pattern. The areas between 19 to 38 cm rainfall zones were determined based on a 30-year (1981-2010) annual average precipitation map obtained from USDA/NRCS (USDA-NRCS, 2012).

Winter Wheat- Winter Wheat-Summer Fallow rotation (Source: USEPA, 2013)

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Year 1	Winter wheat								Fallow	Winter Wheat		
Year 2	Winter Wheat								Fallow			
Year 3	Fallow			Camelina (proposed)					Fallow	Winter wheat		

Winter Wheat-Spring Wheat-Summer Fallow rotation

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Year 1	Winter Wheat								Fallow	Winter Wheat		
Year 2	Winter Wheat								Fallow			
Year 3	Fallow			Camelina (proposed)					Fallow			
Year 4	Fallow			Spring Wheat					Fallow	Winter wheat		

Figure 2.2: Crop rotation pattern in PNW in low (19-38cm) rainfall area

The total available area under each rotational pattern was calculated using Equation 2.3 and 2.4 and converted to annual available acreage for camelina using equation 2.5.

$$A_1 = A(WWF)\ AND\ A(rf) \tag{2.3}$$

$$A_2 = A(WWFS)\ AND\ A(rf) \tag{2.4}$$

Where,

A_1 = Binary raster map layer that follow WWF rotation and lie between 19 to 38 cm rainfall zone = 2.5 million ha

A_2 = Binary raster map layer that follow WWFS rotation and lie between 19 to 38 cm rainfall zone =31.8 thousand ha

A(WWF) = Binary raster map layer that follow WWF rotation obtained from four year of crop data (2009-2012) with criteria = Area(WWFW) OR Area(FWWF) OR Area(WFWW) = 3.08 million ha

A(WWFS) = Binary raster map layer that follow WWFS rotation that satisfied = Area(WWFS) OR

Area(SWWF) OR Area(FSWW) OR Area(WFSW) = 38.3 thousand ha

A (rf) = Binary map layer containing cells that lies between 19 to 38 cm rainfall zone. = 45.8 million ha

The relationship of yield to rainfall was obtained from Hergert et al. (2011) (Equation 2.6).

$$P = \sum \left(\frac{1}{3}A_1 + \frac{1}{4}A_2\right) Y_R \qquad 2.5$$

Where,

P = Total production (kg/yr)

Y_R (kg/ha) = Camelina yield as a function of rainfall (R)

= -1.0821 R^2 + 133.45 R -1189.1 for $12 \leq R \leq 50$ (cm) 2.6

Camelina Meal Demand Assessment

The potential demand for camelina meal as livestock feed in the PNW was calculated assuming that the meal is used at the limits allowed by FDA. The livestock population data were taken from the annual livestock inventory by USDA (USDA-NASS, 2013a; USDA-NASS, 2013b; USDA-NASS, 2013c). Feed consumed by each animal-age group was obtained from animal feed guides published by Washington State University (Platt, 2010), University of Kentucky (Jacob et al., 2011), USDA (USDA-ERS, 2012) and a publication by Cappellozza et al. (2012). The potential demand was compared with potential supply to estimate the percentage of meal that can be used regionally.

RESULTS AND DISCUSSION

Life cycle Analysis

Feedstock Production

Average camelina yield from the farmer's field was recorded to be 1,568.9 kg/ha (1,400 lb/acre). This observed yield was lower than yield estimated using Equation 2.6 for 30 cm rainfall but it was within the 95% confidence interval of research plot data from Washington State University (Painter and Miller, 2009), Montana State University (obtained from correspondence) and University of Idaho (Painter, 2011), where the yield ranged from 1500-1800 kg/ha for the same rainfall zone. However, in the GHGenius model, the yield was estimated to be 1,020 kg/ha ((S&T)[2] Consultants Inc., 2013a, GHGenius 4.03, WorkSheet “Input” Row”111). The recorded inputs from camelina field are shown in Table 2.1.

Table 2.1: Total energy input and GHG emission in feedstock production (Life cycle energy equivalents were obtained from literature)

Item	Amount[1] Per ha	Life cycle energy equivalent	Life cycle energy MJ/ha	GHG equivalent (gCO2e)	Total gCO2e/ha
Diesel	42.0 L	42.5 MJ/L[2]	1786.8	3231/L[3]	135,929
Nitrogen	28.0 kg	51.5 MJ/kg[4]	1442.0	3592/kg[5]	100,833
Phosphorus	16.1 kg	9.2 MJ/kg[4]	148.0	1197/kg[5]	19,360
Sulfur	11.2 kg	1.5 MJ/kg[6]	17.3	798/kg[6]	1,079
Seeds	5.6 kg	30.4 MJ/kg[7]	170.3	189/kg[8]	1,062
Herbicide	5.0 kg	319 MJ/kg[4]	1585.2	25745/kg[5]	128,167
Insecticide	1.6 kg	325 MJ/kg[4]	531.8	29937/kg[5]	49,072
Soil emission					374,710[4]
		Sum	5681.4		810,214.8

[1]Collected farm data; [2](Huo et al., 2008),(Shapouri et al., 2002); [3](DOE-NETL, 2008); [4](Hill et al., 2006); [5] USEPA, 2010; [6] ((S&T)2 Consultants Inc., 2013a), [7] (Shonnard et al., 2010), [8](Sheehan et al., 1998)

Fossil fuel fraction of electricity generation in the PNW was 48%, and the efficiency of electricity generation, transmission and distribution was 32.9% (eGRID, 2012). Electricity was used as source of energy for production operations in this study. Therefore, the fossil fraction of electricity was used while calculating FER.

The field inputs provided by the farmer were similar to the amounts used in field research plots except for nitrogen. The amount of nitrogen used was less than for the field trials. This was because the farmer adjusted the amount of nitrogen applied based on soil test nitrogen before planting which was about 22 kg/ha. If soil nitrogen was added to the additional nitrogen input, the total is comparable to the nitrogen reported in the field trials which varied from 41 to 88 kg /ha (Painter and Miller, 2009; Painter, 2011; Shonnard et al., 2010; Wysocki et al., 2013).

The life-cycle energy input in camelina farming was 2.9 MJ/L of biodiesel (L_bd), which was 33% of the total lifecycle energy input in camelina biodiesel. Nitrogen, herbicide, and diesel were the major contributors (Table 2.4). The GHG emission from camelina farming was 413.3 gCO_2e/ L_bd (Table 2.4). It was 51% of the total emission. The soil emission alone was calculated as 190.7 gCO2e/ L_bd, which constituted 24% of the total emission, 35% of which is N_2O emission from nitrogen fertilization.

Comparing the data with the RFS final rule published in March 2013(USEPA, 2013), the nitrogen input was 44kg/ha, which is higher than the value used in our study. All other inputs were similar to our study. The inputs were adapted from Mcvay and Lamb, 2004; Ehrensing and Guy, 2008; Shonnard et al., 2010. The emission was reported to be 1206 gCO_2e/ L_bd (39 $kgCO_2e$/mmBtu fuel), which is about 3 times compared to our study (413.3 gCO_2e/ L_bd).

Seed Crushing

Oil content of the camelina seed was 34.2%. A mechanical press was able to extract 80% of that oil (0.274 kg of oil/kg of seed crushed). Both oil content and extraction efficiency were lower than reported in the literature. GHGenius assumed the average oil content in camelina to be 43% and used 0.376 kg of oil/kg of seed ($(S\&T)^2$ Consultants Inc., 2013b), while GREET assumed 96% oil extraction efficiency with 0.36 kg oil extracted per kg of seed (ANL, 2012). GHGenius assumed camelina to have similar oil extraction efficiency as canola (96%) based on an industrial survey of canola processing facilities in North America that use mechanical pressing followed by hexane extraction. But, for a farm scale biodiesel production facility, hexane extraction is usually not economically feasible.

The fatty acid profile of the camelina oil showed higher percentages of double and triple bonds (poly-unsaturates) (Table 2.2). Poly-unsaturates are more susceptible to auto-oxidation compared to the single bonds, leading to rancidity in the oil. Higher amount of poly-unsaturates are shown to increase NOx emission during engine tests (Peterson et al., 2000).

Despite higher level of poly-unsaturates, a study by Crowley and Frohlich (1998) showed that the camelina oil stored for 2 years in intermediate bulk containers at ambient temperature had peroxide levels at 4-20 mmoles/kg, which was acceptable for raw oil. The presence of natural antioxidants like polar phenolic compounds (total 128 mg/kg), α-Tocopherol (41±8 mg/kg), γ- Tocopherol (710±19 mg/kg) and δ-Tocopherol (12±3 mg/kg) in the camelina oil facilitates storage stability (Abramovič et al., 2007). A study by Frohlich (1999) showed that the camelina biodiesel remained stable against auto-oxidation for 8 months.

Table 2.2: Fatty acid profile of camelina and canola oil

Fatty acid chain	16:0	18:0	18:1	18:2	18:3	20:0	20:1	20:2	20:3	22:1
Camelina oil	5.4	2.4	16.8	18.8	30.9	1.8	15.2	1.7	1.1	3.5
Canola oil	3.9	2.1	59.3	18.4	7.8	0.0	2.1	0.0	0.0	4.4

16:0 → Palmitic acid, 18:0 → Stearic acid, 18:1 → Oleic acid, 18:2 → Linoleic acid, 18:3 → Linolenic acid, 20:0 → Arachidic acid, 20:1 → Eicosenoic acid, 20:2 → Eicosadienoic acid, 20:3 → Mead acid, 22:1 → Erucic acid

The energy input in the camelina crushing process was 0.4 MJ/L_bd (Table 2.4). GHGenius estimated the crushing energy to be 0.9MJ/L_bd, while GREET estimated 0.59MJ/L_bd. The higher energy input in these two models is attributed to the added process of the hexane extraction method. The GHG emissions from electricity used in camelina crushing was equivalent to 21.0 gCO_2e/L_bd, which was 2% of the total life-cycle energy. The RFS final rule (USEPA, 2013) obtained the crushing data from Shonnard et al., 2010. It estimated the GHG emission from camelina crushing to be 64 gCO_2e/lb of refined oil, compared to 43 gCO_2e/lb of refined oil in our study. The higher emission is again attributed to the added process of the hexane extraction method.

Camelina had a geometric mean diameter of 0.81 mm (with geometric standard deviation of 0.14 mm) compared to canola with a geometric mean diameter of 1.67 mm and geometric standard deviation of 0.13 mm). Camelina seeds were more ellipsoidal with diameter along the longer axis of 1.70 mm and diameter along the shorter axis of 0.4 mm (Figure 2.1). The average hull thickness of camelina was 0.05 mm compared to 0.06 mm for canola. When the crushing energy of camelina was compared with canola, it showed that camelina required 23.9% more energy per kg of seed to crush the seeds, and 46.2% more energy per L of oil expelled. The data confirms the proportionality relationship of seed size and to energy consumption from equations 2.2.

In addition to requiring lower crushing energy, canola also has higher oil content. The average oil content of canola was 40.5% compared to 34.2% for camelina. Out of 40.5% oil in canola, extraction process removed 31.9% of the oil leaving 8.6% in the meal.

Transesterification

For each 100 g of oil, 22 g of methanol (100% excess) and 2.4 g of sodium methoxide was used. The reaction produced 88.6 g of biodiesel and 35.8 g of glycerol. The density of camelina oil was 0.92 g/ml and that of biodiesel was 0.88 g/ml at 20°C. The produced biodiesel met the tested ASTM D6751 specifications except for oxidative stability. Higher levels of poly-unsaturates in camelina oil (Table 2.2) may be the reason camelina biodiesel did not meet the ASTM D6751 specification for oxidative stability. The oxidative stability can, however, be corrected easily with use of an anti-oxidant additive. The effect of the anti-oxidant additive on the LCA was computed in the section “Effects of adding other inputs”.

The energy required in heating, stirring, and methanol recovery during the transesterification process was 2.3 MJ/L_bd (Table 2.3). GHGenius and GREET estimated the energy to be 1.1 MJ/L_bd and 0.86 MJ/L_bd respectively ((S&T)^2 Consultants Inc., 2013b; (S&T)^2 Consultants Inc., 2013c; ANL, 2012). Both systems accounted for the energy expended on methanol recovery. The form of energy input however is different in the three processes. Electricity was used as the only source of energy in this research whereas, GHGenius and GREET used both natural gas and electricity. The total energy invested was 5.6 MJ/L_bd (Table 2.4). The process produced 354.5 gCO_2e/L_bd of GHGs, which is 44% of the total emissions. The NO_x and CH_4 emission from biodiesel combustion was taken from the literature, which was 21.7 gCO_2e/L_bd. The CO_2 emission from biodiesel combustion was excluded from the calculation as it is assumed to be equal to CO_2 captured by the camelina plant during photosynthesis. The March 2013 RFS final rule (USEPA, 2013) has assumed the plant designs for camelina biodiesel plant to be similar to soybean biodiesel plant (402 gCO_2e/L_bd) (USEPA, 2010).

Table 2.3: Energy input and GHG emissions from camelina crushing and transesterification

Inputs	Amount[1]	Life cycle energy	Life cycle energy equivalent MJ/L_bd	gCO2e factor	Total gCO2e/L_bd
Crushing					
Electricity	0.165 kWh/L_bd	10.9 MJ/kWh[2]	1.8	145.7/MJ[3]	86.4
Transesterification					
Electricity	0.212 kWh/L_bd	10.9 MJ/kWh[2]	2.3	145.7/MJ[3]	110.8
Methanol	0.100 kg/L_bd	33.5 MJ/kg[4]	3.3	67.7/MJ[5]	135.3
Sodium Methoxide	0.020 kg/L_bd	31.7 MJ/kg[6]	0.6	7.9/g[6]	153.9
		Total	6.3		400.0

[1] Measured values; [2] Direct unit conversion, (eGRID, 2012); [3](USEIA, 2002a),(USEIA, 2002b); [4] (MI, 2011); [5](USEPA, 2010); [6](Sheehan et al., 1998)

Table 2.4: Total energy input and GHG emission from biodiesel production

Stage	Life-cycle Energy MJ/L_bd	gCO2e /L_bd	Allocation %	Allocated Life-cycle Energy MJ/L_bd	Percentage %	Allocated gCO2e /L_bd	Percentage %
Agriculture	11.9[1]	1700.7[1]	24%	2.9	33	413.3	51
Crushing	1.8[2]	86.4[2]	24%	0.4	5	21.0	2

Transesterification	6.3[2]	400.04[2]	89%	5.6	62	354.5	44
Biodiesel Combustion		21.7[3]	100%			21.7	3
Total (MJ/L_bd)				8.9		810.5	
Biodiesel total energy output (MJ/L_bd)				32.7			
Net energy ratio				3.68			
GHG emission from biodiesel combustion (gCO2e/GJ_BD)				25032.2			
GHG emission from 2005 baseline diesel combustion (gCO2e/GJ_BD)				90,047.4			
Net GHG reduction from biodiesel (%)				72.2%			

[1] From Table 2.1; [2] From Table 3; [3] USEPA, 2010

GHG Reduction, NER and FER Calculation

The total energy input in the production of camelina biodiesel was 8.9 MJ/L_bd, and the total GHG emission was 810.5 gCO$_2$ equivalent/L_bd (Table 2.4). The biodiesel production from the farmer's field was 483.8 L_bd/ha, and, the estimated NER was 3.68 (Table 2.4). This means it takes one unit of energy to produce 3.68 units of energy embodied in camelina biodiesel. When only fossil fuels used in the process were considered, the FER was 4.31. The FER of petroleum diesel is 0.87 (Sheehan et al., 1998). Thus the system is about five times more renewable than the petroleum diesel.

Likewise, the GHG reduction from the production and distribution of camelina biodiesel was 72.2% (Table 2.4), compared to 2005 baseline diesel. This qualifies camelina biodiesel as "advanced biofuel" as per EISA 2007. This value is less than the value by Shonnard et al. (2010) (80%), and GREET (80%) (ANL, 2012), while it is higher than (the value calculated by) Krohn and Fripp (2012) (37-73%) and GHGenius (61.50%) ((S&T)^{2} Consultants Inc., 2013a).

The March 2013 RFS final rule (USEPA, 2013) did not provide the definite number for the GHG reduction from the camelina biodiesel, however it has stated that "the GHG emissions from the camelina-based biodiesel would be similar to the GHG emissions from the soybean-based biodiesel at all stages of the lifecycle but would not result in land use changes as was the case for soy oil as a feedstock", as a result camelina biodiesel could qualify as an "advanced biofuel". The rule also stated that the biodiesel produced from camelina oil is included under the same pathways for which biodiesel made from soybean oil qualifies under the March 2010 RFS final rule (USEPA, 2010).

Effects of Adding Inputs to the LCI

The oil transport was not included in this study as biodiesel production and seed crushing were co-located. However, some biodiesel plants have oil transported and hence the energy used in transportation needs to be added. If exact data are not available than literature values can be used. Sheehan et al. (1998) estimates oil transportation energy to be 0.20 kJ/L_bd/km. ANL (2012) estimates 2.25 kJ/L_bd/ km for feedstock transportation and 3.89 kJ/L_bd/km for biodiesel transportation.

Use of additives to meet ASTM specifications was also included in the sensitivity analysis. Baynox plus (pure) was added as anti-oxidant agent to correct the oxidative stability of camelina biodiesel, as it was shown effective and the cheapest (BAE, 2011). The least amount of Baynox plus required to meet the ASTM D6751 specification was measured to be 600 ppm. This added 21.28 kJ/L_bd energy input to the LCA.[1] When all secondary inputs were included in the base study, the effect on FER was calculated using Equation 2.7.

$$FER' = \frac{E_{output}}{E_{Base} + \ E_{F.T} \times D_{F.T} + E_{O.T} \times D_{O.T} + E_{B.T} \times D_{B.T} + E_A} \tag{2.7}$$

Where,

FER' = FER after adding secondary inputs

E_{output} = Energy per unit of biodiesel = 32.7 MJ/L_bd

E_{base} = Energy input in base case = 8.9 MJ/L_bd

$E_{F.T}$ = Camelina transportation energy per km (Measured value or 2.25 kJ/L_bd/ km)

$D_{F.T}$ = Camelina transportation distance (km)

$E_{B.T}$ = Biodiesel transportation energy per km (Measured value or 3.89 kJ/L_bd/ km)

$D_{F.T}$ = Biodiesel transportation distance (km)

$E_{O.T}$ = Oil transportation energy per km (Measured value or 0.2 kJ/L_bd/ km)

$D_{O.T}$ = Oil transportation distance

E_A = Energy input for an anti-oxidant or other additives per L_bd

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[1] The energy content of Baynox plus is equal to Toulene.(Source: Correspondence to the manufacturer LANXESS Deutschland GmbH, Leverkusen, Germany)

Camelina Production Potential

When camelina is planted as a rotation crop in existing wheat land instead of keeping the land fallow, the available land area for camelina between rainfall 19-38 cm was estimated to be 846,553 ha/yr (2.1 million acres) in the PNW region (Figure 2.3 and 2.4). Adjusting for rainfall, the area has potential to produce 1.6 billion kg of camelina seed. The average production per hectare for all rainfall zones weighted by available acres was found to be 1,895.7 kg/ha. The potential biodiesel production from this land was estimated to be 442.7 million L/yr (117.1 million gal/yr).

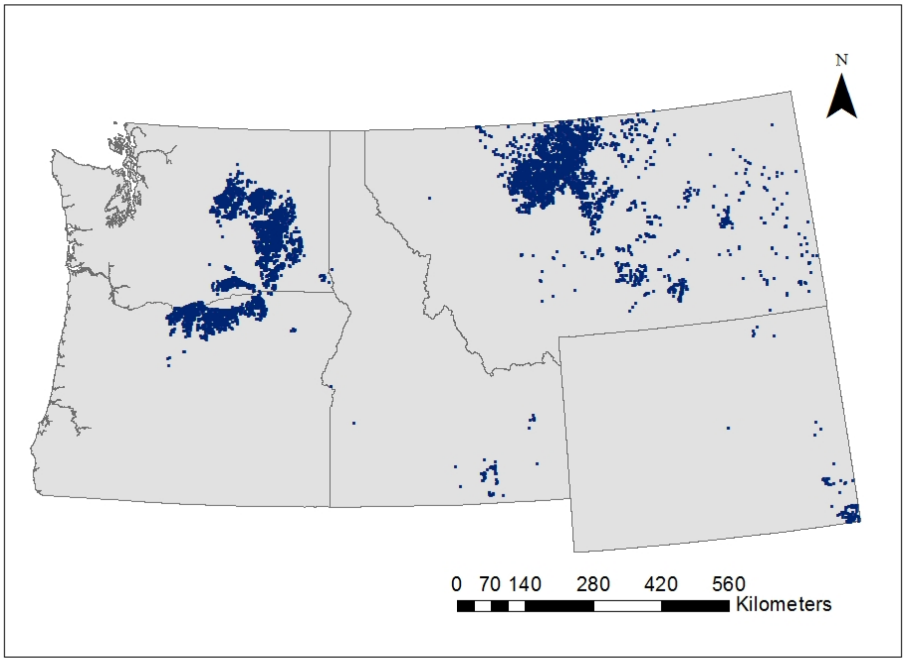

Figure 2.3: Potential camelina cultivation areas in PNW

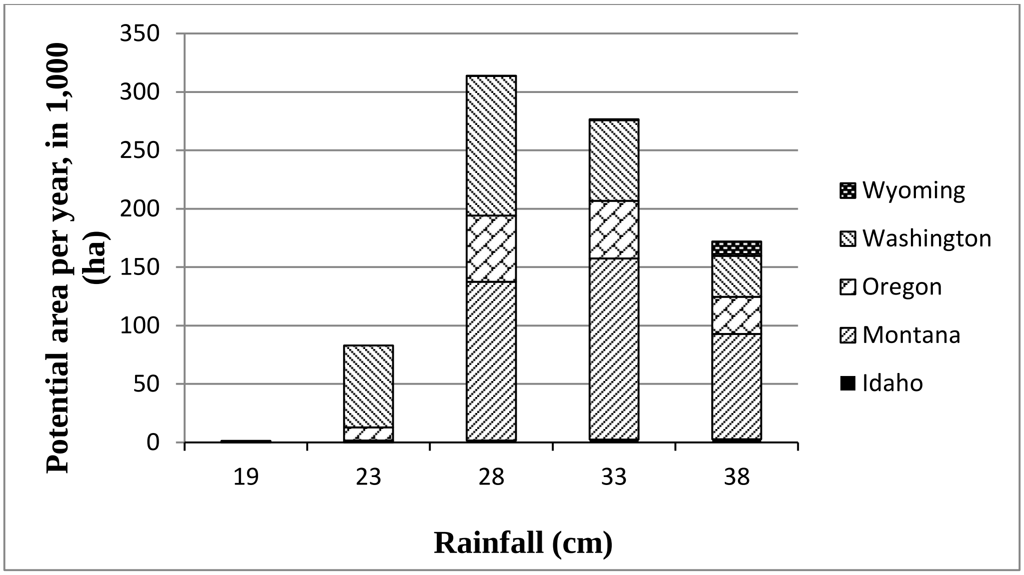

Figure 2.4: Distribution of potential camelina areas across the rainfall zones

The estimated acres in this study agrees with literature values. Shonnard et al. (2010) estimated that over 2 million ha of camelina can be grown in a sustainable manner with no impact on food supply. This corresponds to 3 billion liters of biodiesel per year. Similarly, (Johnson and McCormick, 2010) projected 3.6 million ha of wheat/fallow have appropriate climate, soil profile and market access for camelina production. Based on this land availability, EPA predicted availability of approximately 380 million liters of camelina based renewable fuels (USEPA, 2013). However, farmers are apathetic towards camelina, due to factors like volatile camelina market conditions, competition with canola, low yield, etc (Young et al., 2012).

Camelina Meal

Assuming the allowed percentage of camelina meal would be fed to the livestock population, the total potential consumption was 40 billion kg/yr in the U.S. and 10 billion kg/yr in the PNW (Table 2.5).

Table 2.5: Potential of camelina meal as a feedstock (kg/year)

Region	Broiler Chicken	Layers	Beef Cattle	Hog + Swine	Total
USA	$3.2x10^9$	$2.3x10^7$	$3.8\ x10^{11}$	$2.9x10^8$	$3.9\ x10^{11}$
PNW	$1.0x10^8$	$6.4x10^5$	$9.1\ x10^9$	$2.1x10^6$	$9.6x10^9$

Source: Jacob et al., 2011; USDA-NASS, 2013a; USDA-NASS, 2013b; USDA-NASS, 2013c; USDA-ERS, 2012; Platt, 2010

There is potential of production of 1.2 billion kg of camelina meal as a co-product. This is about 12.1% of the total potential demand for PNW. Therefore, it was concluded that the meal can be consumed in local markets, adding economic benefits to the biodiesel industry.

CONCLUSIONS

The study performed life-cycle analysis on camelina biodiesel produced in the PNW region, estimated potential production, and potential market demand. The data were collected from a camelina farmer, lab experiments, life-cycle models (GREET and GHGenius) and current literature. Comparative analysis on seed size, fatty acid profile and biodiesel quality were made between camelina and canola, a close competitor.

The comparative advantage of camelina over canola is its low moisture requirement and shorter growing season. When rainfall was limited to 38 cm, camelina had a comparative advantage over canola. In higher rainfall areas, canola may be a more lucrative alternative to camelina because of marketability, higher yield and favorable seed size. Seed size analysis showed that smaller seed size required more energy for crushing and experimentation verified that camelina does require 23% more energy compared to canola. Additionally, canola had a better fatty acid profile with higher percentage of mono-unsaturates compared to camelina which had higher percentage of poly-unsaturates. Oil with higher poly-unsaturates tends to increase NOx emissions and reduce oxidative stability. Camelina biodiesel did not meet the ASTM D6751 standard without use of additives.

Despite higher energy for crushing, the net energy ratio (NER) and fossil energy ratio (FER) of camelina biodiesel was found to be 3.68 and 4.31 respectively. The GHG emissions are reduced by 72% from use of camelina biodiesel compared to 2005 baseline diesel. Thus, it was concluded that camelina biodiesel meets GHG reduction threshold of 50% to qualify as the “advanced biofuel”, as set by the Energy Independence and Security Act (2007). Camelina has the potential of production of 1.6 billion kg seeds/yr as a rotation crop in wheat field in PNW. The meal produced as the co-product can be consumed in the local livestock industry, adding benefits to the biodiesel industry. In conclusion, camelina biodiesel is environmentally a good alternative to petroleum diesel, and camelina has a considerable potential as a biodiesel feedstock in the PNW.

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CHAPTER 3: LIFE CYCLE ASSESSMENT OF JET-FUEL FROM CAMELINA OIL

INTRODUCTION

The Energy Independence and Security Act (EISA) has set a target for renewable fuel consumption in the US, a total of 36 billion gallons per year by 2022. Accordingly, the US Federal Aviation Administration (FAA) has set a goal of one billion gallons a year of renewable jet fuel, 1.7% of the predicted total fuel consumption, for the US aviation industry from 2018 (FAA, 2011) . The targeted volume is an aggregate of renewable fuel for the US Air Force, the US Navy and US commercial aviation. One of the main challenges in meeting the goal is the availability of the suitable renewable feedstock. In such context, camelina could be a promising biofuel feedstock based on its drought tolerance, short growing season, and relatively high oil content. It can be grown in lands with even lower than 38 cm (15 inch) annual rainfall, where other crops are not suitable. Camelina also does not compete with food crops, as it has not been approved by FDA for human consumption; however it has approved the use of camelina meal as feed to broiler, beef and swine in limited proportion. In addition, the US Air Force and US Navy have successfully tested camelina jet fuel in a 50:50 blend in its fleet (Sustainable Oils, 2012).

Biodiesel is unsuitable as an aviation fuel due to several reasons including high freezing point, low thermal stability, and low energy density, which does not meet the aviation fuel standard. It has been reported that jet fuel blends containing as low as 1% biodiesel may throw the entire blend off spec for freezing point requirements (Brook, Rickard, and Barratt, 2007), and could lead to unacceptable thermal stability degradation (Wilson, Thom, and Serino, 2007). In fact, the DEF STAN 91-91 (Jet A) standard for jet fuel has limited fatty acid methyl (FAME) content to less than 5ppm. Therefore, camelina has to be converted into jet fuel to use as aviation fuel blend.

The environmental life cycle analysis is important for the commercial production of the camelina jet fuel, to check if it is environmentally sustainable. Studies by (Shonnard et al., 2010) has shown camelina jet fuel to reduce the GHG emission by 50-70%. Stratton et al., (2011), estimate that, when there is no land use change, the lifecycle CO_2 emissions from hydrotreated esters and fatty acids (HEFA) fuel with a soybean oil feedstock relative to emissions from conventional jet fuel range from 31% to 68%. This study is focused on the life-cycle analysis of camelina jet fuel (Jet A) produced in a lab scale facility. The study also includes the general economic analysis of the Jet A fuel produced in that facility.

METHODOLOGY

LCA System Boundary

This LCA covers the following phases of fuel production,

1. Camelina seed production:

   This stage covers the processes and procedures starting from land preparation to farm camelina till harvesting of the seeds. The inputs are fertilizers, herbicides, and fuel for farm machinery operations. This LCA is based on data from a camelina farm and biodiesel plant located in La Crosse, WA. The farmer has been growing dry-land winter camelina (non-irrigated) in 60-120 ha of land for the last 4 years (since 2009) as a rotational crop. Annual rainfall during that period was 30-36 cm, and annual average temperature was -1 to 10 °C. Seeding is done in late October (direct seeding followed by harrowing) and harvested in late March through early April with a combine.
2. Camelina transportation from farm to crushing plant:

   The seed needs to be transported from the farm storage area to the fuel processing plant for the manufacture of bio-fuel. Since the seed transportation is highly variable depending on individual farms and processing plants, the energy incurred in seed transported in expressed in per mile of distance travelled.
3. Oil extraction and bio-fuel production:

   Generally, a modern day bio-fuel processing plant consists of oil extraction facilities as well. The oil was cold pressed using an oil expeller, and the oil is used to produce bio-fuel. The energy and materials inputs in oil expulsion and bio-fuel processing like electricity to operate machineries and required chemicals are included to calculate the energy balance. The mass based co-product allocation method is used for energy allocation between the co-products produced during oil extraction and bio-fuel processing, as it is consistent with Pradhan et al., 2009. Seed meal is produced as a co-product during oil extraction, whereas the CO_2 and unreacted fatty acids are produced during bio-fuel processing.

4. Bio-fuel transportation and distribution.

   This is the last stage of the LCA. Since the distance for bio-fuel transportation and distribution to end users is highly variable, the energy incurred on it is also expressed as per mile of distance travelled.

Data Collection

The data collection methodology for agricultural inputs and seed crushing are discussed in the previous chapter. The same data were used for the calculations in this chapter.

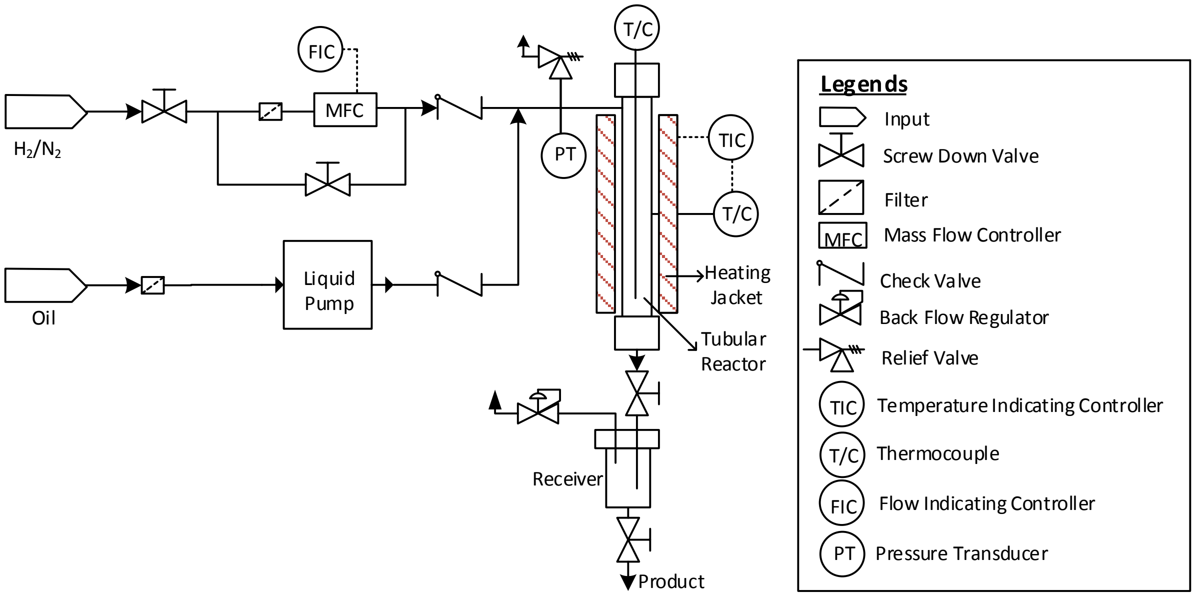

Figure 3.1: Schematics of continuous tubular reactor (Adapted from Parr Instruments Company, 2013)

Jet-fuel was prepared using de-oxygenation and fractional distillation of camelina oil. The energy required to conduct these thermo-chemical processes were measured with the experimentation in the small lab scale facility. The de-oxygenation was conducted in a 5403 continuous tubular reactor 60x4.8x2.5 cm (Parr Instrument Company, Moline, Illinois)(Figure 3.1). The temperature of the reaction tube was maintained at 350-370 ˚C, and N_2 pressure at 687 kPa (100 psig) (Madsen et al., 2013 and Snåre et al., 2008). Palladium on alumina, 0.5% (Pd/Al_2O_3,) 3.2mm pellets, unreduced (Sigma-Aldrich, St. Louis, MO) was used as catalyst. The Pd catalyst was activated in the same continuous tubular reactor, at a temperature of 100 °C, and H_2 was passed through for 1 h, at 100 psi, to reduce from Pd(II) oxidation state, i.e. commercially available form, to Pd(0). The reduction to Pd(0) is required as Pd(0) platform facilitates the deoxygenation reaction. The camelina oil was pumped into the reactor at the rate of 1ml/min. When the oil level reached the level of catalyst packing it was held for three hours to provide adequate residence time to complete the reaction. The flow was maintained at 1 ml/min after that. The samples were collected every six hour.

The samples were sent for GC-MS to Anatek Labs, Inc, Moscow ID, to measure the quality and quantity of the hydrocarbon. The fractional distillation was performed in a VDS3000 Manual Vacuum Distillation System (Koehler Instrument Company, Inc, Bohemia, Houston, TX), at 300 °C. The electricity used during the processes was measured using a Watts up Pro power data logger, 120 VAC/15Amps (Electronic Educational Devices, Inc., Denver, CO).

The catalyst gets gradually deactivated and needed to be replaced or rejuvenated after certain time. As reported by Bernas et al., 2010, Madsen et al., 2013 and Madsen et al., 2011, deactivation occurs mainly due to coking. Coking is the formation of carbonaceous residues, which cover the active sites of the catalyst or block the pores (Forzatti and Lietti, 1999). The study did not make a separate measurement of the surface area of the catalyst to determine the extent of coking in the catalyst after the run. The deactivation of the active sites of the catalyst was checked from the quality of product, i.e. the extent of deoxygenation, during the run. The extent of deoxygenation was determined from the GC-MS results of the products taken every six hours. The estimation of clogging was determined from the change in flow rate of the product, during the run. However, 24 hrs of run is short to determine the catalyst deactivation. Therefore, the deactivation rate of the catalyst was assumed to be similar as Bernas et al., 2010, Madsen et al., 2011and Madsen et al., 2013, as their reaction conditions, the reactor and the feedstock were similar. The data were analyzed using a spreadsheet. The produced fuel was tested for selected properties of ASTM D7566 specifications such as acidity, sulfur content, flash point, density, freezing point, and net heat of combustion. The data for energy invested in transportation of camelina, camelina oil, and bio jet fuel were obtained from The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model (GREET) v1_2013 (ANL, 2012).

For the economic analysis, the cost of the continuous tubular reactor was obtained from the Parr Instrument

Company, and the fractional distillation system from the Koehler Instrument Company, Inc. The costs of all other materials were obtained from regional vendors and wholesalers, through personal communication. The depreciation rate of the fixed investments was assumed to be 5%. The annual maintenance cost was assumed be to 5% of the total fixed costs. The insurance cost was not included.

RESULTS AND DISCUSSION

Life Cycle Analysis

The produced fuel was tested for the above mentioned ASTM D7566 specifications for Jet A (Table 3.1). The freezing point was 2°C higher than required by the specification. Therefore, the fuel did not meet the specifications and is not suitable to use as commercial aviation fuel in its neat form. Further investigations and experimentation is required to correct the property of the fuel, for e.g., cracking to shorten the chain length of the hydrocarbons or lowering the distillation temperature to avoid longer chain hydrocarbons in the jet fuel etc., could lower the freezing point and help meet the standard for freezing point.

Table 3.2: ASTM 7566 specifications

Specifications		Measured Values	Standard values
Acidity, total mg KOH/g	Max	0.075	0.1
Sulfur, total mass %	Max	0	0.003
Flash point, °C	Min	45	38
Density at 15°C, kg/m^3		820	775-840
Freezing Point °C	Max	-38	-40
Net heat of combustion, MJ/kg	Min	42.98	42.8

However, the energy balance and GHG emission of the produced fuel was calculated. The yield of the jet fuel was found to be 244.57 L_jet/ha (0.17L_jet/kg of seed). In comparison, the yield of the camelina biodiesel was 477.41 L_bd/ha, which is almost double the yield of jet fuel. The energy invested in the production of the camelina seeds and transportation to the storage was 3.29 MJ/L_jet (MJ per liter of jet fuel) (Table 3.3).

Likewise, the energy input in the oil press was 0.27MJ/L_jet (Table 3.3). The energy required for hydroprocessing, including deoxygenation and fractional distillation was found to be 22.35MJ/L_jet (Table 3.3). The yield from the hydrocarbons suitable for Jet A was 51.5% (Table 3.2).

Table 3.2: Composition of the product from de-oxygenation

Compound ID	Mol. Form.	Percentage (%)
2,2,4,6,6-pentamethyl-heptane	$C_{12}H_{26}$	38.8
2,2,4,4, Tetramethyloctane	$C_{12}H_{26}$	3.6
1-cyclohexymethyl-cyclohexane	$C_{15}H_{28}$	2.7
2,6,7 Trimethyl-decane	$C_{13}H_{28}$	2.4
2,2.3,3 Tetra methyl-pentane	C_9H_{20}	2.1
1-cyclohexymethyl-cyclohexane	$C_{15}H_{29}$	0.8
Pentadecane	$C_{15}H_{32}$	0.7
4-methyl heptane	C_8H_{18}	0.6
Total		51.7

The camelina oil contains primarily C18 fatty acid chains, primarily unsaturated, with only about 10 per cent being saturated. About 52% of the fatty acids are polyunsaturated, primarily linoleic (18:2) and linolenic (18:3), and 32% are monounsaturated, primarily oleic (18:1) and eicosenoic (20:1). Gosselink et al., 2013 proposed cracking, β-elimination, hydrolysis, and C-C scission (Figure 3.2), as possible pathways for deoxygenation of triglyceride under N_2 atmosphere.

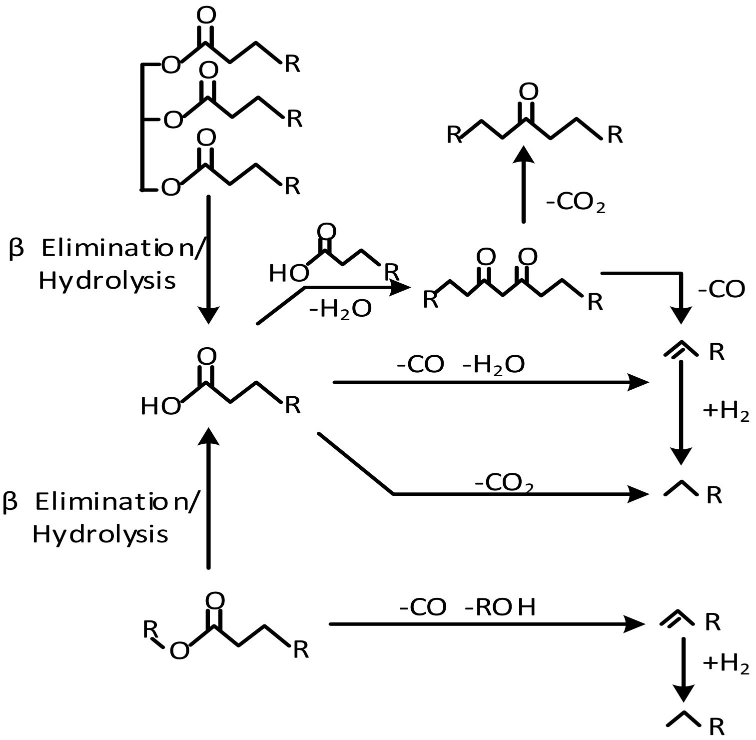

Figure 3.2: Proposed reaction mechanism for triglyceride in N_2 environment (Adapted from Gosselink et al., 2013**)**

The deoxygenation reaction was relatively steady (Figure 3.3) for up to 24 hours, as the oxygen content in the product was more or less equal during the run. This means that the blocking of active sites in the catalyst was negligible.

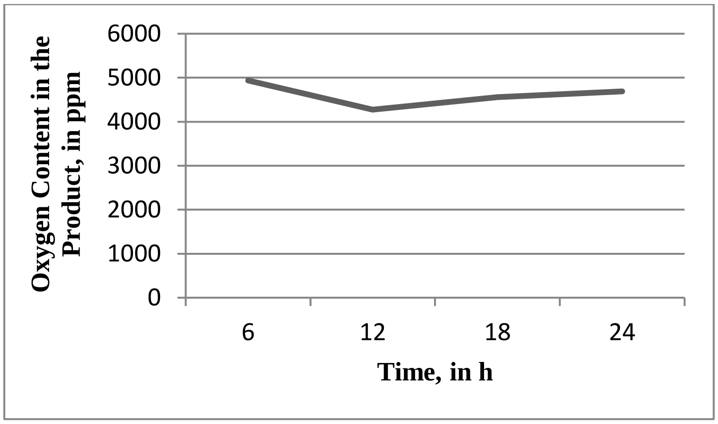

Figure 3.3: Oxygen content in the deoxygenated product

The flow rate of the product was observed to be steady during the 24 h run. Therefore, it was concluded that the occurrence of blocking of the pores was negligible as well. Therefore, the deactivation of the catalyst during the 24 h run was determined from the literature.

After accounting for all the energy invested in the process, the net energy ratio of the fuel was estimated to be 1.36 (Table 3.3). The jet fuel production and combustion reduced the GHG emission by 56.6% compared to the conventional Jet-A. The GHG emission from Jet A was obtained from Stratton et al., 2010. The energy input and GHG emission in each stages of life cycle was given in Figure 3.3.

Table 3.3: Total inputs and emissions from camelina jet fuel production

Energy input	Total Energy input (MJ/L_jet)	Jetfuel share (MJ/L_jet)	GHG Emission (gCO_2e/L_jet)
Agriculture	11.90	1.74	419.80
Crushing	1.80	0.26	20.99
Hydroprocessing	20.63	11.03	486.77
Combustion (NOx & CH_4)			168.92
Total	34.33	13.03	1096.48
Total energy output of Jet Fuel (MJ/L_jet)			35.18
Net energy ratio (NER)			1.36
Net energy value (MJ/L_jet)			9.28
GHG Emission from Conventional Jet Fuel (gCO_2e/L_jet)			2528.40
GHG Reduction (%)			56.6

The life cycle equivalent and GHG emission of items are given in Appendix A.

The energy input in the transportation of camelina seed from storage to biofuel processing plant and transportation of jet fuel to the end user is not estimated in the base study. It is estimated as the energy input per km of distance travelled. The energy input of 2.25 kJ/L_jet/ km was used for feedstock transportation and 3.89 kJ/L_jet/km for biodiesel transportation, as assumed by GREET. The oil transport was not included in this study as the biofuel processing plant and seed crushing facility were at the same building. However, some biofuel plants may have to get oil transported. The model used by Sheehan et al. (1998) separated the crusher from the biodiesel conversion facility, so their inventory included the energy required to transport the oil to the biodiesel plant, which was 0.20kJ/L_jet/km.

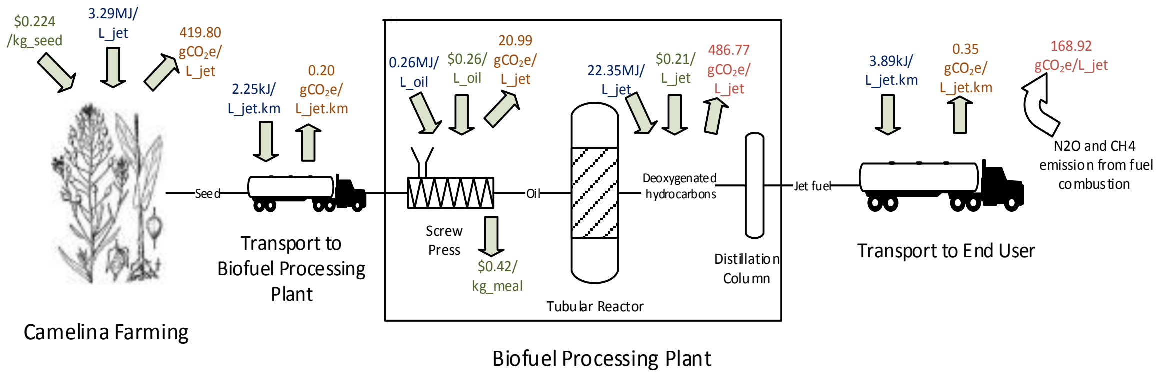

Figure 3.3: Life cycle process flow diagram for camelina jet fuel

Further experimentation will be carried out in order to make the fuel meet the specifications. The results will be added to the thesis, when finished.

Cost of Production

The economic analysis of the process was performed on the basis of the experiment, in the laboratory scale. The assumptions in the analysis are:

1. No transportation costs included, as this study is focused on the cost of production of jet fuel in laboratory facility. The transportation cost was given as $/km of fuel transported later in the results.
2. The jet fuel is manufactured in the laboratory scale continuous flow tubular reactor.
3. Labor cost is not included in the calculation.

The equipment and set up costs were included as the capital costs (Table 3.4). The operating costs included fertilizers, seed, fuel, herbicides etc.; oil pressing cost and biofuel processing costs, i.e., catalyst costs, utility costs etc. (Table 3.4). The camelina oil is the feedstock. The camelina seed cost $0.212/kg to produce (UI, 2012). The operating cost of the oil press was $0.12/L ($0.47/gal of oil). The price of the camelina meal was assumed to be $0.4/kg, which was produced as the co-product from oil press. It was assumed that camelina meal is sold in the livestock industry, and provides revenue. The cost of biofuel processing, i.e. deoxygenation and fractional distillation was $0.47/L of jet fuel. The total operating cost for the production of camelina jet fuel was found to be $2.46/gal of jet fuel. The cost incurred during each life cycle stages was given in Figure 3.3. The revenue of the co-products from the deoxygenation and fractional distillation were not considered, as it required further processing for it to be saleable in the market, which further adds cost and energy to the system. Including the fixed costs such as the initial investment, depreciation etc., the total cost of production is $15.52/gal of jet fuel. If it was assumed that the camelina oil was bought from the market, then at the market price of $2.49/gal of camelina oil the variable and total cost of jet fuel production was found to be $3.66 and $16.72 per gal of jet fuel, respectively. The current market of jet fuel is $3.62/gal. At the current price, the cost of production at the lab scale is around 4 times greater than the conventional jet fuel. However, this calculation was based on a lab scale facility, which is not suitable for commercial production.

Table 3.4: Bill of materials required to produce jet fuel

Capital Cost		
Item	**Nos.**	**Cost ($)**
Reactor	1	75,000
Fractional Distillation System	1	12,328
Oil press	1	9,652
Hose (20ft. Long)	1	60
Pressure gauge	1	17.5
Regulator	1	315.25
Storage tanks	4	1179
Variable Cost		
Item	**Unit**	Rate
Camelina Seed	/kg	0.212
Nitrogen gas	/kg	0.007
Hydrogen gas	/kg	0.409
Catalyst	/kg	0.002
Electricity	/kWh	0.053

There are some published works in the economic analysis of renewable jet fuel (hydrotreated), not necessarily camelina as a feedstock. However, these estimates are based on the model. Winchester et al., 2013 reported, if soybean oil is used as a feedstock, it is found that meeting the aviation biofuel goal in 2020 will require an implicit subsidy to biofuel producers of \$2.69/gal of renewable jet fuel. If the aviation goal can be met by fuel from oilseed rotation crops grown on otherwise fallow land, the implicit subsidy required will reduce to \$2.22/gal of renewable jet fuel. This estimate is based on the 282 million liter per day capacity plant from Pearlson, 2011. When the price of soybean oil is \$2.46/gal, Pearlson, 2011 estimated that the gate cost of hydroprocessed jet fuel to be \$3.80/gal for a 6,500 barrel per day plant. Likewise, a report by the Agriculture Council of Saskatchewan estimated the cost of production of jet fuel as \$0.80/L (\$3.03/gal_jet), for a 230 million L per year processing facility (ACS, 2012). This was estimated for the province of Saskatchewan, and assuming the camelina is farmed in dry areas, unsuitable for other crops, and feedstock is available in sufficient amount to run the plant in its full capacity.

CONCLUSION

Alternative aviation fuel is in high demand, due to the concerns for environmental impacts and energy independence. Camelina jet fuel could be the viable alternative to conventional jet fuel, as camelina can be grown in low rainfall lands, unsuitable for other crops. This study deals with the life cycle analysis of the camelina jet fuel produced in a laboratory scale facility. The jet fuel was produced via deoxygenation of the camelina oil in an inert environment, in the presence of Pd/Al_2O_3 catalyst. The jet fuel fraction was separated with fractional distillation. The produced jet fuel was tested for ASTM 7566 specifications for Jet A. The produced jet fuel did not meet the specifications, which indicates the necessity of further experimentation and investigation. However, the energy balance and GHG emission analysis of the produced fuel was performed. The NER of the fuel was found to be 1.36, and the GHG emission reduction was 57% compared to the conventional jet fuel. As the fuel did not meet the specifications, the fuel can not be used for commercial purpose.

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CHAPTER 4: SUMMARY AND CONCLUSIONS:

Feasibility of making Biodiesel and Jet Fuel from Camelina grown in the Pacific Northwest were studied using Life Cycle Analysis tools. The biodiesel was produced in a farm scale biodiesel plant owned by a farmer in the Pacific Northwest of Washington and Jet Fuel was produced at the University of Idaho laboratory. Based on the comparable system boundary as previous studies, the net energy ratio of the production of camelina biodiesel was found to be 3.68. The CO_2 equivalent GHG emission was estimated to be reduced by 72% compared to petroleum diesel, which satisfies the requirement necessary for camelina biodiesel to be considered a renewable fuel derived from biomass-based diesel as mandated by Renewable Fuel Standard (RFS2). For camelina biodiesel to be considered as an advanced biofuel, the RFS2 program of U.S. Environmental Protection Agency (US-EPA, 2010) requires it to reduce the GHG emission by 50% compared to petroleum diesel.

The jet fuel produced did meet the ASTM D7566 specification for the alternative aviation fuel except for its freezing point. So technically, the fuel cannot be claimed as aviation fuel at its pure state. However it is possible that the fuel will meet the specifications with cold flow additives or when blended with conventional jet fuel. Further experimental trials are needed to improve the quality of the fuel to meet the standards. However, the energy input and GHG emissions were estimated, and the NER was found to be 1.36, while GHG emission reduction compared to conventional jet fuel was 57%. Although, it satisfies the minimum requirement of 50% GHG reduction, as set by Renewable Fuel Standard (RFS2), it cannot be used as commercial fuel, as it did not meet ASTM D7566 specifications.

The potential of camelina production in Pacific Northwest region, as a rotational crop, was estimated. The estimation was calculated using GIS by determining the fallow areas in wheat-fallow rotation pattern which lie in low rainfall zone (19-38cm rainfall). It was estimated that 846,500 hectares (2.1 million acres) of land is available in the PNW region that could potentially produce 1.6 billion kg of camelina seed, equivalent to 405 million L of camelina biodiesel.

DISCUSSION AND FUTURE WORKS

In this study, the jet fuel produced did not meet the ASTM D7566 specifications. Further experimental trials could not be conducted due to lack of time. In future, the study will focus on conducting more experiments to improve the quality of the fuel to meet the specifications.

Although the theoretical calculation shows the considerable amount of land available as potential areas for camelina cultivation, there could be some limitations to it. According to the farmer’s experiences, the wheat yield was found to be lower when planted after camelina in wheat-camelina rotation. The reason could be the depletion of soil moisture resulting from the camelina cultivation, which renders the soil dry for subsequent crop. However, there are many advantages to planting camelina in the fallow season. It breaks the pest/insect cycle for the wheat. The tap root structure of camelina loosens the soil layer, which improves porosity of soil, facilitates water percolation, and improves aeration. Therefore, further research is required to study the effects of camelina cultivation on subsequent crops. This would be helpful to determine if camelina is a suitable rotational crop in wheat fallow rotation for low rainfall areas.

APPENDIX A

Life cycle energy equivalent and GHG emissions of the inputs

Item	**Life Cycle Energy**	**Unit**	**Source**	**GHG emission (gCO_2e)**	**Unit**	**Source**
Diesel	42.4	MJ/L	Huo et al., 2008; Shapouri et al., 2002	90.0	/MJ	DOE-NETL, 2008
Nitrogen Fertilizer	51.5	MJ/kg	Hill et al., 2006	3592.4	/kg	USEPA, 2010
Phosphorus Fertilizer	9.2	MJ/kg	Hill et al., 2006	1197.5	/kg	USEPA, 2010
Sulfur Fertilizer	1.5	MJ/kg	(S&T)2 Consultants Inc., 2013	154.0	/kg	(S&T)2 Consultants Inc., 2013
Seeds	30.4	MJ/kg	Hill et al., 2006	189.3	/kg	Sheehan et al., 1998
Herbicide	319.0	MJ/kg	Hill et al., 2006	25745.9	/kg	USEPA, 2010
Insecticide	325.0	MJ/kg	Hill et al., 2006	29937.1	/kg	USEPA, 2010
Electricity	10.9	MJ/kWh	Direct unit conversion, eGRID, 2012	145.7	/MJ	USEIA, 2002
Methanol	33.5	MJ/kg	MI, 2011	67.7	/MJ	USEPA, 2010
Sodium Methoxide	31.7	MJ/kg	Sheehan et al., 1998	7.9	/g	Sheehan et al., 1998
Catalyst	12.1	MJ/kg	Sheehan et al., 1998	646.9	/kg	Sheehan et al., 1998
Hydrogen gas	181.4	MJ/kg	Spath and Mann, 2001	11888.0	/kg	Spath and Mann, 2001
Conventional diesel				949.3	/L	USEPA, 2010
Biodiesel				21.7	/L	USEPA, 2010
Alternative Jet fuel emission				168.9	/L	Santoni et al., 2011
Conventional Jet fuel Emission				2528.4	/L	USEPA, 2008