

Production of Multiple Biofuels from Whole Camelina Material: A Renewable Energy Crop

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Camelina sativa is a cool-season oil seed crop that has been proven to produce various biofuels. The present study investigated the technical possibilities of using whole camelina biomass as a model feedstock in a biorefinery. This investigation examined the possibilities of using camelina seeds as a source of oil for biodiesel, sugars for ethanol, and meal for one-portfolio products. The camelina harvest residues (straw) can serve as the main source for green sugars. This study found that the energy input for the whole biorefinery process was 25.1 MJ/L ethanol, while the energy output was 54.3 MJ/L ethanol. The net energy ratio of 2.16 MJ/L ethanol was found to be competitive with other energy crops. The process was environmentally friendly, and it reduced greenhouse gas emissions by 40% if the produced biodiesel replaced petroleum diesel. The seed meals and glycerin were found to be a good source of revenue as high value-added products and can provide an additional revenue of \$1/kg of produced oil.

Keywords: Camelina seed; Meal; Enzymatic hydrolysis; Biodiesel; Net energy ratio; Bioethanol

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INTRODUCTION

Biofuels (mainly ethanol) derived from lignocellulosic materials (Alkasrawi *et al.* 2013), industrial waste (Gurram *et al.* 2015; Alkasrawi *et al.* 2016), agricultural waste (Elum *et al.* 2017), and energy crops (Pimentel and Patzek 2005) have been receiving a great amount of attention. Energy crops, such as sugar beets, sugar cane, corn, and sweet sorghum, are vital resources for fuel today and in the future. Although there is a debate concerning the use of some crops for food *versus* for biofuel (Young 2009), energy crops are considered major players in biofuel production. These energy crops include sugar cane in Brazil and corn in the U.S. (Enciso *et al.* 2016).

Many studies have investigated various types of energy crops as alternatives to petroleum fuel. One interesting and promising crop is *Camelina sativa* with its rich content of oil and high yield of harvest residues (straw). Keske *et al.* (2013) modeled the economic feasibility of growing the *C. sativa* oil seed crop in the Western U.S. to produce a value-added protein feed supplement and biofuel. Moreover, Ciubota-Rosie *et al.* (2013) performed a detailed study of *C. sativa* characteristics to fully evaluate its potential as a biofuel source.

Camelina can be grown in a variety of climatic and soil conditions. It has many agronomic advantages, such as a short growing season and a tolerance for cold weather, droughts, semiarid conditions, and low-fertility or saline soils Moser (2012). Additionally, it has lower water, pesticide, and fertilizer needs compared with other oil seed crops (Ciubota-Rosie *et al.* 2013).

The water-deprived regions of the Western U.S. and colder climates of the upper Midwestern U.S. create a perfect niche for farmers to utilize camelina as a rotation crop. Camelina fits into the Western U.S. crop rotation of wheat, followed by corn and fallow (Keske *et al.* 2013). Currently, the farmers of the Midwest grow extensive amounts of corn and rotate with soybeans that are later marketed for vegetable oil or biodiesel. If utilized as a commodity for both biodiesel and protein meal for livestock, camelina provides farms and communities with a source of economic diversification. Some estimates indicate that the U.S. state of Montana alone could support between 0.8 million hectares and 1.2 million hectares of camelina per year Moser (2012).

The present study investigated the technical possibility of producing ethanol and biodiesel from the whole camelina crops (The straw and the seeds). The study was divided into two different stages. The first stage investigated (lab scale experiments) the optimal conditions for sugar production and evaluated their potential for fermentation into ethanol as well as biodiesel production. In the second stage, a technical and economic evaluation was performed by rigorous process simulation using AspenPLUS software for mass and energy calculation. Ultimately, the whole crop biorefinery concept promoted the first-generation biofuels to be economic competitive with second-generation biofuels pathways with respect to energy yield and GHG reduction.

EXPERIMENTAL

Chemical Composition Analysis

The chemical compositions of both the seeds and straw were analyzed. Montana State University Northern provided the *C. sativa* seeds and straw substrate (Havre, MT). Raw seeds and straw were stored at room temperature in sealed plastic bags. The moisture contents for both the seeds and straw were determined by a standard gravimetric method by placing the samples in a pre-weighed moisture bottle (pre-dried in an oven at 100 °C for 30 min) (Gurram *et al.* 2016). Samples were then kept in an oven at 105 °C overnight. After cooling to room temperature, the bottles were weighed again to determine the moisture content.

The sugar and lignin composition of the straw, seed, and meal were estimated according to a method developed by the National Renewable Energy Laboratory (NREL). A dried oven sample of 0.3 g added to 3 mL 72% (w/v) sulfuric acid and diluted using distilled water to 87 mL. The solution was mixed well and kept at 30 °C in a water bath for 1 h. The material was autoclaved at 121 °C for 1 h to hydrolyze all sugars from cellulose and hemicellulose part. The solid residue after hydrolysis was filtered, washed and dried for lignin and ash determination.

The carbohydrate contents of the seeds and straw were determined according to the National Renewable Lab method (Sluiter *et al.* 2010), which was followed by analysis with a Dionex ICS 3000 and 4 mm x 250 mm Carbopac PA1 column ion chromatograph (Thermo Scientific Waltham, MA, USA).

The oil yield was determined after weighing the oil produced after the filter press. The protein content was measured using the Kjeldahl method (Horwitz 1975) by using a nitrogen-to-protein conversion factor of 6.25.

Sugar Production Platform

Sugar exists in whole camelina crops as free soluble sugars as part of the seed or as a main structural component in the form of cellulose and hemicellulose in the straw.

In the sugar production platform, several lab-testing methods were proposed to produce various sugars from the whole camelina crop. The free sugars in the seeds were obtained by treatment with water and weak acid, while the structural sugars in the straw were extracted *via* chemical, thermal, and biological methods.

Extraction of the Soluble (Non-structural) Sugars from the Plant Seeds

Soxhlet extraction is an efficient technique for soluble sugar extraction and provides a high yield recovery (Hymowitz *et al.* 1972). In this study, 2 g of camelina raw seeds or pressed meal were placed in a Soxhlet apparatus (TICH Scientific, Orlando, FL USA) for 4 h using 200 mL of either acetic or formic acid as the main solvent. Various concentrations of the solvents were used to determine the optimum solvent concentration and type. The concentrations of acetic acid were 1%, 5%, 10%, and 15%, while for formic acid they were 1%, 5%, and 10%. The extractions were done as follows. Two grams of camelina seed substrate (or meal) were put into a 30 mm x 100 mm Whatman glass Microfibre filter (Sigma Aldrich, Orion Township, MI, USA), which was then placed into a 45/50 mm Soxhlet chamber (TICH Scientific, Orlando, FL, USA). This chamber was inserted on one end into a round bottom flask, while the other end was put into a 45/50 mm glass condenser. The solvent was set to a moderate boil and each extraction was run for approximately 4 h. All of the analyses were done in triplicate, and the extracted sugars were analyzed with the ionic chromatographic method described later in this paper.

Extraction of the Structural Sugars from the Straw

The structural sugars are the sugars that make up the cellulose and hemicellulose of straw. Sugar recovery from the straw was investigated with thermal pretreatment and enzymatic hydrolysis. Both methods were extensively studied with the goal of achieving high sugar yields and low production costs. The methods for enzymatic hydrolysis and thermal pretreatment were studied separately.

Thermal pretreatment

The straw specimens were ground using a Wiley Mill with a 40" sieve (TICH Scientific, Orlando, FL USA). Ten grams of biomass were run in a Parr reactor (Parr Instruments, Moline, IL, USA) at 150 °C for 16 min. Sulfuric acid was added as a catalyst at different ratios with respect to the solid load, which were 1 w/v%, 2 w/v%, and 3 w/v%. The liquid fraction was separated *via* filtration with Whatman filter paper (TICH Scientific, Orlando, FL USA) and then frozen for the sugar analysis. The solid residue was collected, stored, and refrigerated for later use in enzymatic hydrolysis.

Enzymatic hydrolysis

The effectiveness of various initial concentrations of the following commercial enzymes was evaluated: Novozyme Cellic(R)CTec2 cellulase, α -amylase, and amyloglucosidase. One gram of dried seed meal was crushed and placed into a 250-mL

media bottle, followed with pH adjustment to 4.8 by using 0.05 M citrate buffer. Different enzyme combinations were tested as follows: 20 μ L, 50 μ L, 80 μ L, and 100 μ L of cellulase alone; 80 μ L of cellulase with 50 μ L of each α -amylase and amyloglucosidase in all experiments; α -amylase and 50 μ L of each cellulase and amyloglucosidase; and α -amylase alone. Hydrolysis was done in sealed bottles incubated in shaking incubator for 72 h at 50 °C. Samples were withdrawn at regular intervals. Experiments were repeated in triplicate as described by Gurram et al. (2015). All enzymes were generously supplied by Novozymes A/S, Bagsvaerd, Denmark.

Fermentation

The sugar produced (soluble free sugar and structural sugar) was evaluated for ethanol production in a fermentation process. The sugar stream was diluted to the level that the yeast could tolerate (150 g/L). Industrial yeast FermPro™ (Ferm Solutions Inc., Danville, USA) was used for the ethanol fermentation experiments. One milliliter of frozen yeast concentrate was pre-cultured for 16 h at 37 °C in yeast peptone dextrose media that contained 20 g/L glucose, 20 g/L peptone, and 10 g/L yeast extract. The solid-free Pantone Plus Series (PMS) sugar solution was supplemented with the following additional nutrients according to Tanner (2007): 10 g/L KH_2PO_4 , 20 g/L $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 4 g/L $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, 200 mg/L $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$, 20 mg/L $\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$, 200 mg/L $\text{CoCl}_2 \cdot 2\text{H}_2\text{O}$, 2 mg/L d-biotin, 5 mg/L p-aminobenzoic acid, 5 mg/L Nicotinic acid, 5 mg/L calcium pantothenate, 10 mg/L pyridoxine-HCl, 5 mg/L thiamine-HCl, and 10 mg/L lactoside. Fermentation was performed in 500-mL mini bioreactors (BioBundle Applikon Biotechnology, Foster City, USA) in triplicate with a total working volume of 350 mL. The fermenter assembly with the nutrient rich sugar solution was sterilized at 121 °C for 20 min in an autoclave (Tuttnauer/Brinkmann VWR International, Arlington Heights, USA). The fermentation experiments were performed at a pH of 5.0, 37 °C, and 200 rpm with a dissolved oxygen value of 10%. Two-milliliter sample aliquots were drawn from the sample port at different intervals using sterilized syringes.

Sugar and Ethanol Determination

The sugar and ethanol concentrations were monitored with ion chromatography (Dionex ICS 3000, Thermo Scientific, Waltham, USA). The optical density was measured at 595 nm using a Thermo Scientific Evolution 605 UV/Vis Spectrophotometer to determine the cell density over the course of fermentation.

Biodiesel Production

The biodiesel was produced according to a well-established method described by Soriano and Narani (2012). One liter of camelina oil was produced by filter pressing camelina seeds and heating them to 55 °C. The catalyst was prepared with the ratios of methanol and NaOH to oil 1:30 (weight : volume) and allowing the solution to mix gently for 20 min. This led to the formation of sodium methoxide, which is a proven catalyst for biodiesel production. The prepared catalyst was added slowly to the filtered and heated oil at 55 °C and gently stirred for 1 h. The mixture was left overnight until a separation between the glycerol and biodiesel was clearly distinct. The oil was gently decanted from the glycerol, and the yield was calculated. The biodiesel washed gently and subsequently dried before estimating the final yield.

Conceptual Design of the Biorefinery Process

The configuration of the present process (Fig. 1) represents the overall biorefinery concept for the production of multiple biofuels utilizing the whole camelina crop as the main feedstock. The conceptual design was developed from several studies to provide a basis for the mass and energy balances of the process (Gurram *et al.* 2016). The main target was to achieve production of multiple biofuels (ethanol and biodiesel) within the same process configuration.

The conceptual design of the process was based on the daily processing of 30,000 t of whole camelina crop. The assumptions of the biorefinery capacity is based on Inbicon demo commercial facility Inbicon (Larsen 2012). The seeds (10,000 t, 10% dry matter) and straw (20000 t, 50% dry matter) arrive separately, as separation is done in the field. The seeds enter a unit for oil extraction and subsequently utilized for biodiesel production. The meal (pressed seeds) is utilized as animal feed or burned to generate heat for the facility. The extracted oil was used for biodiesel production, which is implemented using a well-established method. The straw was thermally treated at 150 °C using sulfuric acid as a catalyst. After thermal pretreatment, the solid fraction is hydrolyzed enzymatically to produce sugars and mixed with the liquid fraction prior to alcoholic fermentation. Another stream of the sugar production platform (extracted from the seeds) is added to the fermentation step. The residual lignin can be burned to generate steam for use in the proposed process.

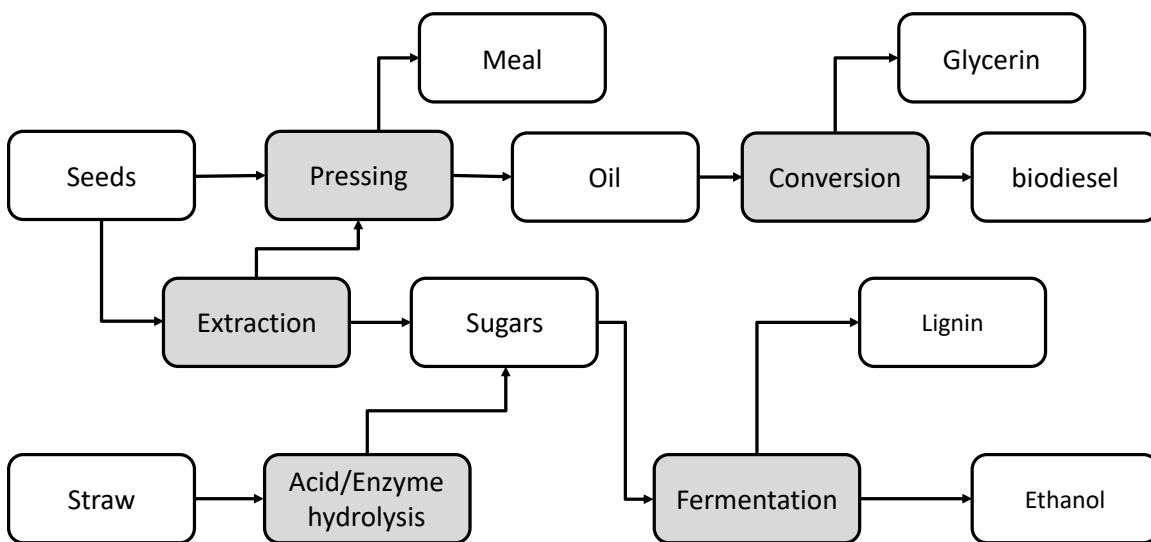


Fig. 1. Overall schematic flow sheet for the conceptual design of the biorefinery for the production of multiple biofuels and high value-added products. The conceptual design was the base case scenario for the process simulation.

Process Simulation

Based on the proposed conceptual design, the whole process was simulated in AspenPLUS v8.4, (AspenTech, Houston, TX, USA) to calculate the overall process efficiency and feasibility. The simulation methods utilized by AspenPLUS were developed by the National Renewable Laboratory (NREL) and used in a similar study by Gurram *et al.* (2016). The NREL method developed a physical and chemical property data bank for ethanol production from lignocellulosic feedstock. A flow sheet was first developed in

AspenPLUS according to the conceptual design proposed in Fig. 1. All of the process inputs were specified in AspenPLUS as described in the conceptual design. The basis for the sugar yield, ethanol production, and biodiesel yield was specified in AspenPLUS according to the results obtained in the first part of this study.

RESULTS AND DISCUSSION

Chemical Composition Analysis

The whole camelina crop seed, seed meal, and straw contain a potential amount of stored sugars in the seed and structural sugar in the form of cellulose in the straw (Table 1). The seeds were about 10% (based on dry weight) free soluble sugars, which was determined by the compositional analysis. Soluble sugars are easy to extract and do not require severe chemical or thermal pretreatment. This fact has a major economic impact on process scaling because this type of process requires less energy consumption, and thus it decreases the operational costs compared with thermal and enzymatic hydrolysis. The soluble sugars in the seeds comprised 15% of the available sugar for fermentation from the whole plant (seeds and straw). Assuming that the amount of energy required to recover the soluble sugar from the seed is marginal compared with that required for thermal pretreatment of the lignocellulosic sugar (Schmer *et al.* 2008; Kumar *et al.* 2009), this suggests that a 15% reduction of the required energy is possible with respect to the energy input per volume of ethanol produced (kJ/L ethanol). Table 1 could be used to determine the main product value of the crop. For example, the seeds contain a substantial amount of (30%) is very competitive when compared with other oil crops, such as rapeseed, soybean, and oil palm (Mattsson *et al.* 2000). This is a substantial amount of oil provide an economical feedstock to produce biodiesel for transportation.

Table 1. Dry Matter Compositional Analysis of the Whole Camelina Crop

Straw (Plant Residues)	
	wt.%
Cellulose	50
Hemicellulose	20
Lignin	15
Ash	10
Others	5
Total	100
Seeds	
Oil	30
Protein	30
Glucose	18
Other sugars	2
Ash	10
Others	10
Total	100
Meal	
Oil	5
Protein	42
Carbohydrates	42
Ash	10
Total	99

Sugar Production Platform

Soluble sugar recovery from the seeds and meal

The highest possible yield for the sugar recovery was achieved at yield values of 30 mg/g and 34 mg/g for the seeds and meal, respectively. Both the formic and acetic acid proved to be viable and mild catalysts for lignocellulose feedstock fractionation (Schneider *et al.* 2016a,b; Li *et al.* 2017). An interesting finding was that more sugar was recovered from the meal than from the seeds. This was likely because the mechanical extraction for the oil provided a higher surface area for the solvent to recover sugars. Additionally, the oil extraction did not negatively affect sugar recovery but enhanced it. This was an interesting finding because sugar extraction requires less energy demand, and thus lowers the production costs compared with lignocellulosic feedstock (Jørgensen *et al.* 2007; Viikari *et al.* 2012). This factor will definitely have a major impact on the final production cost of biofuels derived from whole camelina crops.

Sugar production from the straw

The whole plant straw was investigated for sugar production using several scenarios. The sugar recovery from thermal decomposition using H₂SO₄ resulted in the hydrolysis of the hemicellulose into a liquid fraction. Several studies have also shown sulfuric acid to be a very promising catalyst with a high yield recovery (Söderström *et al.* 2003). The optimum sugar recovery was obtained at 1% H₂SO₄, 160 °C, and a total time of 16 min. This could have corresponded to 50% of the theoretical glucose. The aim was about 50% of the theoretical yield to avoid the generation of inhibitors, as the residues would be further hydrolyzed enzymatically. These results were found to be very competitive with other fraction methods reported for similar feedstocks, such as straw (Schneider *et al.* 2016b, 2017). The residue solid obtained after acid hydrolysis mainly contained the complex cellulose-lignin structure subjected to cellulase hydrolysis for complete cellulose recovery during enzymatic hydrolysis.

Enzymatic Hydrolysis

The highest sugar yield was obtained at an enzyme load of 80 µL after 56 h. These results corresponded to 98% of the theoretical glucose in the residues after acid pretreatment in the Parr reactor. This agreed with several other results from studies that used similar feedstock residues after acid pretreatment (Saha *et al.* 2005; Chen *et al.* 2008; Schneider *et al.* 2017), and it is possible for the residue to be further treated with enzymatic hydrolysis. An interesting finding was that the enzyme load was lower than values reported in previous studies. For the enzymatic hydrolysis of acid-pretreated straw, acid pretreatment in the Parr reactor facilitated the open structure of the cellulose, which led to better enzymatic accessibility. Higher conversion rates of cellulose were obtained with the pretreated residues because a larger surface of the pretreated cellulose was available for enzymatic hydrolysis.

Ethanol Production in the Fermentation Process

All of the sugars produced from the various processes were mixed and underwent alcoholic fermentation. The results of the ethanol fermentation showed that the yield was 93% of the theoretical yield. This was most likely because less inhibitors were generated during sugar production from the straw.

Low inhibitor generation is always a positive for the process because it impacts the theoretical yield of ethanol (Kotarska *et al.* 2015; Muktham *et al.* 2016). This yield was very competitive compared with similar studies performed with other energy crops. Although alcoholic fermentation is a well-established process, this test was done as a baseline for the initial parameters in the AspenPLUS simulation.

Oil Recovery and Biodiesel Production

The recovered oil from the seeds was about 30% of the dry mass and provided a substantial amount of oil for biodiesel production (Table 2). A substantial amount of biodiesel was obtained, and the remainder was glycerol, which provided another profitable aspect to the life cycle analysis of this crop. The biodiesel production is a well-established technology, although several researchers have recently discussed a novel catalyst for higher yields and a better fuel quality. Soriano and Narani (2012) characterized the properties of biodiesel from camelina oil using the same seed used in this work. Their work discovered that a few of the biodiesel properties of camelina are similar to those of sunflower biodiesel properties, such as the flash point, cloud point, cold filter plugging point, kinematic viscosity (40 °C), and oil stability index. Camelina biodiesel has been blended with a standard JP-8 jet fuel and successfully used by the U.S. Air Force to test fly F/A-18 Super Hornet and A-10 Thunderbolt II fighter jets (Liu *et al.* 2013).

Conceptual Design and Process Simulation

The process flow sheet developed in the conceptual design was simulated in AspenPLUS for mass and energy balance calculations based on the initial compositional analysis of both the seeds and straw. Technical and economic analyses of lignocellulosic ethanol based on process flow sheet simulations are an attractive tool for studying the overall efficiency and process profitability (Shemfe *et al.* 2015). For the energy balance evaluation, the net energy value (NEV) and the net energy ratio (NER) were used in the present work. The NEV is the difference between energy input and output, whereas the NER is the ration of net energy value to the energy input.

Tables 2 and 3 shows a summary of the overall energy and mass balances. The feed inputs presented in Table 2 represent the theoretical amount of the original feed feedstock.

Table 2. Simulation Results of Mass Balance for the Feed Flow and the Biofuels Outflow

Feed	Dry Ton/Day Input	Biodiesel L/Day	Ethanol L/Day
Straw (Dry matter 50%)			
Cellulose	10000	-	3208
Hemicellulose	4000	-	1283
Lignin	3000	-	-
Seed (Dry matter 10%)			
Oil	3000	1890	-
Glucose	1800	-	485

Table 3. Simulation Results of Energy Balance and the Net Energy Value

Energy Balance	Ethanol MJ/L Ethanol	Biodiesel MJ/L Ethanol
Energy in:		
Downstream Processing	3.30	1.95
Upstream Processing	12.1	6.2
Utilities	1.50	0.05
Energy out		
Biofuels	22.9	22
By-product	9.40	-
Net Energy In	16.9	8.2
Net Energy Out	32.3	22
Net Energy Value	15.4	10

Results from a simulation of the daily processing of 20,000 t of straw (50% dry matter content) and 10,000 t seeds (10% dry matter content) showed a total of 4976 L of ethanol produced. There was about 2% to 3% sugar loss because of decomposition in the acid pretreatment of the straw. After fractionation of the lignocellulosic materials, the solid residues contained mainly lignin with a heat value to be used as energy input displacement. Sugar extraction from the seeds provided an additional 1620 (theoretical amount is 1800) t of sugar, which was mainly glucose (Table 2). The combination of sugars recovered from the straw and seeds was fermented to fuel ethanol in a 12000-m³ fermentation vessel. In the downstream processing, two distillation columns were connected in series with a high purity ethanol rectifier by shifting the azeotrope point under vacuum distillation to produce 98% ethanol. The mass and energy balance calculations showed that the processes for the conversion of sugar to ethanol (sugar extraction and fermentation) required 3.3 MJ/L ethanol. The downstream processing and ethanol distillation and rectification required 12.1 MJ/L ethanol. An additional 1.5 MJ/L ethanol was depleted by heat and work requirements from the pumps and heat exchangers (Table 3). The overall energy consumption for ethanol production was about 16.9 MJ/L ethanol, whereas biodiesel required less energy input, 8.2 MJ/L ethanol. The overall NEV were 15.4 and 10 ML/L Ethanol for both ethanol and biodiesel production respectively. The All of the energy input results for ethanol production were very similar to the results obtained by Gurrām *et al.* (2016) because the same model was used and testing was done in the same lab. The total energy requirement for the whole biorefinery is 25.1 MJ/L ethanol, which was lower compared with the total energy yield of 54.3 MJ/L ethanol. The total energy yield was based on the heat values of the ethanol, lignin, and biodiesel. This process had a very competitive NER 2.16 compared with the NER of corn grain biomass 1.25 Morales *et al.* (2015) and soybean biodiesel 1.93 (Tilman *et al.* 2006). Table 4 shows that the NER value of camelina is very competitive compared to other energy crops. This is a truly interesting value that can be expected to encourage biofuel industries to further investigate the commercial benefits of camelina crop.

Interestingly, the present finding agrees with several studies on camelina crop. Krohn and Fripp (2012), calculated that the camelina biodiesel reduced greenhouse gas (GHG) emissions by 40% to 60% compared with petroleum diesel (Table 4). A different study conducted by Miller and Kumar (2013) found that the GHG reduction and net energy ratio (NER) for camelina-based biodiesel ranged from 30 g CO₂ eq/MJ to 82 g CO₂ eq/MJ and 1.0 MJ/MJ to 2.3 MJ/MJ, respectively. Reducing the GHG emissions by 82 g CO₂

eq/MJ was found to be very competitive with petroleum-derived diesel and made the whole crop environmentally friendly as an energy crop. However, Krohn and Fripp (2012) calculated that a seed yield of 403 kg/ac to 807 kg/ac must be maintained to sustain a reduction in the GHG. Chen *et al.* (2015) reported that tuning the practices of a crop management system would lower the production price if a camelina–wheat rotation was implemented.

Table 4. Net Energy Ratio and GHG for the Whole Camelina Bioprocess in the Biorefinery Platform Compared to Other Competing Crops

Energy Crops	Net Energy Ratio (NER)	g CO ₂ eq/MJ	Reference
Camelina Ethanol & biodiesel	2.16	40 ^b	Current study Krohn and Fripp (2012) ^b
Corn ethanol	1.25	90	Morales <i>et al.</i> (2015)
Sugar beet ethanol	1.4	106	Morales <i>et al.</i> (2015)
Sugarcane ethanol	4.4	50.6	Morales <i>et al.</i> (2015)
Jatropha Biodiesel	1.73	56.7	Kritana <i>et al.</i> (2006)

In the present study, the commercial benefit of the byproducts from the proposed process, such as meal and glycerin, were also investigated. A higher profit would be obtained with the production of both meal and glycerin. Tisserat *et al.* (2014) investigated the use of camelina meal with coffee tree woods a composite material. The meal properties included a 5% omega-3 fatty acid content, 40% protein content, and metabolizable energy of approximately 3 KJ/kg. High concentrations of glucosinolates, which have a potential health hazard at high doses, have been found inside camelina seeds. Lawrence *et al.* (2016) and Koçar and Civaş (2013) stated that camelina meal exhibits a good growth performance in dairy heifers (compared with dry distilled grain) when using it as a protein supply. Currently, the U.S. Food and Drug Administration allows 10% camelina meal (by weight) in beef cattle and broiler chicken feed. Research on the effects of camelina meal on animal livestock is still in progress but has provided reliable evidence that camelina may be used not only as a biofuel, but as a rich protein additive. Camelina seed meal and glycerin byproducts can provide an important source of revenue to improve the overall process economy. Very little information is available on the nutritional quality and economic value of camelina seed meal. Fortunately, soybean meal is very similar to camelina meal with respect to the nutritional quality (protein content). Therefore, the available data on soya meal was used to anticipate the economic revenue of camelina meal and its use as an animal feed (Ryhänen *et al.* 2007). The estimated price of soy meal and glycerin is \$0.28/lb and \$0.15/lb, respectively. Neibergs *et al.* (2016) reported that the price of camelina meals varies between \$100 to 350/ton, whereas, the price history presented by Heming (2005) for glycerin in US market ranged between \$100 and 120/ton. This would correspond to a monetary value of \$1/kg meal of produced oil. Interestingly, both products (meal and glycerin) provided an energy displacement of 42 MJ/lb, according to Krohn and Fripp (2012).

Camelina has been shown to grow successfully under cooler and arid climates with the end goal of harvesting the seeds as a viable biofuel and protein additive. The complex capabilities of camelina oil and seed meal have proven to be a diverse commodity

for Midwestern farmers in the expanding biodiesel market. Because it is so complex, camelina is paving new roads in research and development, and only time will tell its true potential as a biodiesel feedstock and healthy food additive.

CONCLUSIONS

1. The process for the production of multiple biofuels from whole camelina crops is considered feasible. The process exhibits improved energy yield and environmental suitability relative to other crop-based biofuel processes.
2. The process analysis suggests that this process is profitable and sustainable because of the production of other valuable byproducts, mainly meal and glycerin.
3. Both of the aforementioned commodities can be sold directly, without further preprocessing. Lignin was also recovered as a byproduct, and it can be used as a heating fuel in the biorefinery.

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