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Economic perspective of ethanol and biodiesel coproduction from industrial hemp

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ABSTRACT

In this study, the economics of producing biofuels from an industrial hemp *(Cannabis sativa)* genotype – 19m96136 was investigated. A lignocellulosic biofuel plant, hourly consuming 85 metric tons of hemp biomass was modeled in SuperPro Designer®. The integrated bioenergy plant produced hemp biodiesel and bioethanol from lipids and carbohydrates, respectively. The structural composition of the industrial hemp plant was analyzed in a previous study. The data obtained was used to simulate feedstock composition in SuperPro Designer®.

The simulation results indicated that Hemp containing 2% lipids can yield up to 3.95 million gallons of biodiesel annually. On improving biomass lipid content to 5 and 10%, biodiesel production increased to 9.88 and 19.91 million gallons, respectively. The breakeven unit production cost of hemp biodiesel with 2, 5, and 10% lipid containing hemp was $18.49, $7.87, and $4.13/gallon, respectively. The biodiesel unit production cost when utilizing 10% lipid-containing hemp was comparable to soybean biodiesel at $4.13/gallon. Furthermore, sensitivity analysis revealed the possibility of a 7.80% reduction in unit production cost upon a 10% reduction in hemp feedstock cost. Furthermore, industrial hemp was capable of producing between 307.80 and 325.82 gallons of total biofuels per hectare of agricultural land than soybean.
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1. Introduction

Increasing climate change concerns along with efforts to reduce greenhouse gas emissions has demanded biobased energy to substitute fossil fuel consumption (Khounani et al., 2019). Bioethanol and biodiesel are two major biofuels used in the transportation sector. In 2019, 15.78 billion gallons of fuel ethanol or bioethanol was produced, which is a 44% increase in a decade (Energy, 2021). The feedstock category of fuel ethanol market is dominated by corn. Nearly 39% of total corn harvested was utilized for bioethanol production (Year: 2019) and more than 95% of fuel ethanol produced was from corn starch (Energy, 2021; USDA, 2020a). A wide variety of lignocellulosic feedstocks for the production of bioethanol, including wood-based materials, herbaceous biomass, and agricultural residues are being actively pursued (Cheng et al., 2019a, b; Sipos et al., 2010). Although lignocellulosic biofuel processing shows high production yields, economic factors limit its long-term sustainable production (Raud et al., 2019). However, recent developments including solvent liquefaction methods, hydrothermal and biological methods of pretreatment show a promising future for the lignocellulosic biofuels industry (Kim et al., 2019; Mahmood et al., 2019). Furthermore, ongoing thorough fundamental research and technoeconomic feasibility studies aid in overcoming the obstacles in long-term commercialization.

For centuries, Hemp (*Cannabis sativa* L.) has been used for various biobased products due to its high-quality fiber, and plethora of phytochemicals (Andre et al., 2016). However, more recently, applications have been broadened to building/construction materials, textile, essential oils, paper industry, and as CBD (cannabidiol) substrates (Harris et al., 2008; Leizer et al., 2000). Nevertheless, hemp is a promising feedstock for the production of biofuels due to its high biomass and oil yields (Li et al., 2010). Hemp has excellent adaptability to a wide range of agro-ecological conditions and can be grown on marginal lands (Struik et al., 2000). Due to its agricultural versatility as well as oil and carbohydrate

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Nomenclatures

TAG	Triacylglycerol
FAME	Fatty acid methyl esters
UPC	Unit production cost
ha	Hectare
LHW	Liquid hot water
UPC	Unit production cost
MT	Metric ton
gal	Gallon

coproduction capability, hemp is highly regarded as a potential feedstock for sustainable biorefinery. However, the cultivation of industrial hemp for private or commercial applications was prohibited in the U.S. due to the presence of trace amounts of the intoxicating constituent THC (δ-9 tetrahydrocannabinol) (Cherney and Small, 2016), present in marijuana varieties of *C. sativa* L. The federal restriction on the cultivation and processing ("Agricultural Act" farm bill) was lifted in 2014, which allows individual institutions to grow and process industrial hemp (Das et al., 2017). Henceforth, the market value of hemp-derived products in the U.S. was predicted to reach over $23.7 billion by 2023 (Lee, 2019).

Hemp cultivation can yield dry matter between 10 and 15 tons/ha (Schluttenhofer and Yuan, 2017). The harvested biomass is estimated to contain more cellulose (40–43%) than other agricultural feedstocks (37–39%), including bioenergy sorghum, corn stover, and sugarcane bagasse (Cheng et al., 2019a, b; Kim et al., 2016; Wang et al., 2018). To address the economic sustainability of a feedstock for bioethanol, efficient low-cost pretreatment is required to breakdown complex cellulosic components of the biomass. Several technologies, including physical, chemical, and physicochemical approaches, have been studied to increase cellulosic sugar recovery and ethanol yields. Widely used steam pretreatment can disrupt the physiochemical linkages between lignin and carbohydrates and prevent the degradation of fermentable sugars (Cheng et al., 2019a, b). This approach requires less capital investment than other chemical methods (Cheng et al., 2019a, b), hence, steam or hydrothermal pretreatment has been regarded as greener and more economical technology for the production of cellulosic ethanol.

Research on hemp biomass for bioenergy production has been promising. Recent studies on industrial hemp genotypes reported glucan content in the range of 35–40% and xylan between 10 and 16% (Das et al., 2017; Viswanathan et al., 2020; Zhao et al., 2020). Glucose yield reported by Zhao et al. (2020) ranged between 53 and 71% upon LHW (Liquid hot water) pretreatment followed by enzyme hydrolysis. Whereas yields of more than 75% were obtained in our study when LHW was combined with disk milling, followed by enzymatic hydrolysis (Viswanathan et al., 2020). Importantly, the concentration of known inhibitors in the hydrolysate was well below their inhibitory limits. Subsequent ethanol fermentation using the hydrolysate obtained from hemp biomass produced yields up to 75% (Zhao et al., 2020).

Biodiesel is primarily produced from plant oils and waste oil by transesterification (Navas-Anguita et al., 2019). The annual biodiesel production has increased by 234% since 2009, to 1.72 million gallons in 2019. Soybean oil accounted for about 60% of the total feedstock consumed for biodiesel production (EIA, 2020). In 2019, approximately 30.80 million hectares of agricultural land in USA was used for soybean crop cultivation, producing 3.55 billion bushels of soybean (USDA, 2020b). However, given the economic driver of soybean is its high-quality protein, the relatively low oil yield per hectare of soybean limits the expansion of soybean biodiesel production. Hence, with the current production scheme, market growth to continue displacement of fossil fuel is challenging. One approach to overcome this bottleneck in meeting the expected demand for plant lipids for the bioeconomy is to introduce genetic variation to selected feedstocks that are designed for the synthesis of vegetative lipids (Vanhercke et al., 2014).

Free and acylated fatty acids in the form of triacylglycerol (TAG) serve as substrates for many industrial bioproducts including biodiesel, lubricants, and plastics. While lipids play a pivotal role in plant cells, the level of TAG accumulation is minor in vegetative tissues. However, as our understanding of the genetic and biochemical underpinnings governing lipid metabolism in plant cells continues to improve (Bates et al., 2013), this knowledge will enable researchers to translate and improve TAG accumulation in vegetative tissues in crop feedstocks (Vanhercke et al., 2019; Xu and Shanklin, 2016; Zale et al., 2016). For example, metabolic engineering approaches have led to approximately 20% TAG accumulation in tobacco leaves (Andrianov et al., 2010). A hectare of production of this lipid accumulating tobacco would harvest significantly more oil than would be realized from a hectare of an oilseed crop. Thus, such a biobased platform holds great potential for generating inexpensive value-added biomass for the bioeconomy.

In our previous study, above ground biomass (stems and leaves) of hemp genotypes were collected from wild populations ('ditch weed') across the state of Nebraska or selectively bred. The biomass was analyzed for lipid content, both TAG and total fatty acids, along with structural carbohydrates (Viswanathan et al., 2020). The results revealed that hemp-based TAGs were either rich in palmitic acid or linoleic acid. The fatty acid profile of the hemp genotypes named SC (Seward County), LC (Loup County), CBD (CBD- Hemp) was similar to crude seed oil of soybean and corn, containing primarily linoleic acid (~50%). The capacity of plant biomass to contain TAG is proportional to biodiesel yield. The TAGs present in hybrid cross variety named 19 m (19m96136) and CBD-hemp were approximately 2 and 25% of total lipids respectively.

Integrated lignocellulosic biofuel production schemes are interesting, due to multiple bulk fuel/chemical production from one feedstock resource. Huang et al. (2016) performed a technoeconomic analysis on integrated biofuels production from lipidcane – a sugarcane feedstock. The minimum selling price of biodiesel was estimated between $0.59 and 0.89/L, when lipid concentration in the biomass was at 20 and 2%, respectively. The results showed the integrated biofuel production from energy crops can lead to better cost structure, process economics, and biofuel yield than conventional seed oils such as soybean or other lignocellulosic biomass including corn stover. The fatty acid profile and levels observed in hemp biomass is an attribute that demonstrates the crop has great potential as a feedstock for the bioeconomy. To assess this potential, this study details an economic analysis on utilizing industrial hemp to produce ethanol and biodiesel in an integrated biofuel plant. To date, this is the first study focusing on the costs of integrated biofuels productions using industrial hemp. In this research, Lipids present in the feedstock was extracted and transesterified to produce biodiesel. Lipid-free biomass is then processed through chemical-free hydrothermal pretreatment combined with disk refining, followed by enzymatic hydrolysis, to produce bioethanol.

2. Methods

2.1. Feedstock composition

As communicated above, biomass from five industrial hemp genotypes was analyzed for lignocellulosic sugars, ash, lignin, and triacylglycerol (TAG) content (Viswanathan et al., 2020), following protocols outlined in The National Renewable Energy Laboratory's analytical procedure – *NREL/TP-510-42618* (Sluiter et al., 2008). The hemp genotype, 19m96136 (19 m), was a hybrid derived from genotypes collected from York County and Loup County in Nebraska. The total carbohydrate content of 19 m hemp was measured at 45.32% (Glucan: 34.70%; Xylan 10.62%). The total extractives (water and ethanol) and ash content were measured at 20.00% and 3.67% respectively. The total lignin content of 19 m was estimated at 17.92%. Only 2% of total lipids present in genotype 19 m was TAG. Palmitic (16:0) and stearic acid (18:0) were the two major fatty acids observed in the fatty acid methyl ester or biodiesel obtained from extracted TAG, which was quantified by gas chromatography (Viswanathan et al., 2020).

The industrial hemp hybrid was grown at The Agricultural Research station, Mead, NE, USA. At the time of harvest, the plant recorded a maximum plant growth height among all varieties at 220.67 cm. Furthermore, high stover dry matter and total dry matter yields at 6923 kg/ha and 8396 kg/ha, respectively, were obtained from 19 m variety (Viswanathan et al., 2020). High stover yield per cultivable land area implies high carbohydrate yield, and hence this variety was chosen as the feedstock material for bioenergy production economic analysis.

2.2. Process description

The SuperPro Designer® (Version 10, Intelligen Inc., Scotch Plains, NJ, 2017) platform was used for process design, simulation, and technoeconomic analysis. Unit operations and their respective operating parameters were selected based on the lipid-cane TEA model (Huang et al., 2016) along with other models developed for related biodiesel and ethanol production platforms (Haas et al., 2006; Humbird et al., 2011; Kwiatkowski et al., 2006). Table 1 lists key process parameters for unit operations utilized in the SuperPro Designer® process simulation. Figs. 1 and 2 detail the complete process flow diagram of the bioenergy facility. The plant was assumed to consume 85 metric tons of biomass every hour, operating at 330 days annually. Biodiesel was the primary product, while bioethanol, glycerol, and energy (electricity) were the coproducts obtained from the plant. The plant lifetime was assumed at 20 years with 2 years spent on plant construction, with a calculated income tax rate at 35%. The biofuels production plant has three major sections, including feedstock preparation, ethanol production, and biodiesel production. Lipids were extracted from the biomass in the feedstock preparation section (Fig. 2). The extracted lipids and lipid-free biomass were then transported to the biodiesel and ethanol production sections, respectively.

The Lipid-free biomass from the feedstock preparation section undergoes sugar conversion procedures involving hydrothermal pretreatment, disk refining, and enzymatic hydrolysis, converting structural carbohydrates to simple monosugars. Followingly, the reducing sugars were fermented by unicellular ethanol-red yeast, under anaerobic conditions, producing bioethanol. Separation of ethanol was then performed through series of distillation columns and then purified by passing through molecular sieves. The remaining post-processed biomass was used for energy production.

In the biodiesel production section, the lipids were converted to biodiesel with base catalyst, through two-stage transesterification reactors. The derived esters were subsequently separated and purified resulting in the end product – biodiesel. The coproduct stream containing glycerol undergoes further processing to produce glycerol coproduct.

Table 1
Operating process parameters and plant properties utilized for SuperPro Designer® process simulation.

Item	Value
Operating parameters	
Feedstock moisture content	30%
Lipid separation (Tricanter centrifuge)	95%
Lipid separation (Filter press)	98%
Pretreatment solid loading	50%
Pretreatment operating temperature	180 °C
Enzymatic hydrolysis conversion	85%
Inoculum vol per fermentation vol	10%
Fermentation efficiency	90%
Fermentation time	72 h
Distillation stage efficiency	35%
Product purity (Stage-1)	60%
Product purity (Rectifier)	90.00%
Product purity (Molecular sieves)	99.50%
Transesterification conversion	90.00%
Methanol to lipid molar ratio	3:1
Neutralization conversion	95.00%
Neutralization residence time	1 h
MeOH Distillation stage efficiency	40.00%
H2O Distillation stage efficiency	80.00%
Glycerol purity	85.00%
Boiler steam pressure	60 bar
Boiler heat losses	5.00%
HP steam final pressure	10 bar
HP steam Condensate-free isentropic efficiency	74.37%
LP steam final pressure	5 bar
LP steam Condensate-free isentropic efficiency	63.80%
Plant process parameters	
Lang factor	3
Project lifetime	20 years
Construction period	5 years
Income tax	35%
Depreciation period	20 years
Working capital	5% of FCI

2.2.1. Feedstock preparation segment

Feedstock preparation includes washing, grinding, and separation of lipids from the biomass (Fig. 1). Hemp biomass was first washed using recycled water, to remove any soil and dust materials. Washed biomass was subsequently ground and squeezed through a screw press to extract aqueous juice. The extracted juice containing lipids, water, and some biomass fractions was then centrifuged through a tricanter, to separate all three fractions. The lipid fraction was concentrated via a plate and frame filtration system (Stavropoulos and Petrides, 2020). The lipid-free biomass from the centrifuge was combined with mainstream biomass from screw press and conveyed to the lignocellulosic sugar breakdown segment. The concentrated lipids were stored for downstream biodiesel production. The aqueous stream was utilized for energy production.

2.2.2. Lignocellulosic sugar breakdown segment

The sugar breakdown segment involves a pretreatment and an enzymatic hydrolysis of steps that lead to the harvest of monosaccharide sugars (Fig. 1). The pretreatment reactor was a hydrothermal process to mitigate biomass recalcitrance (Cheng et al., 2019a, b). Here, the biomass with 50% solid loading, was treated with high-pressure steam at 180 °C for 10 min (Table 1), followed by a sudden release of pressure down to 1 atm to manifest extensive defibration and rupturing of fibers (Cheng et al., 2020). The pretreated biomass was then subjected to enzymatic hydrolysis

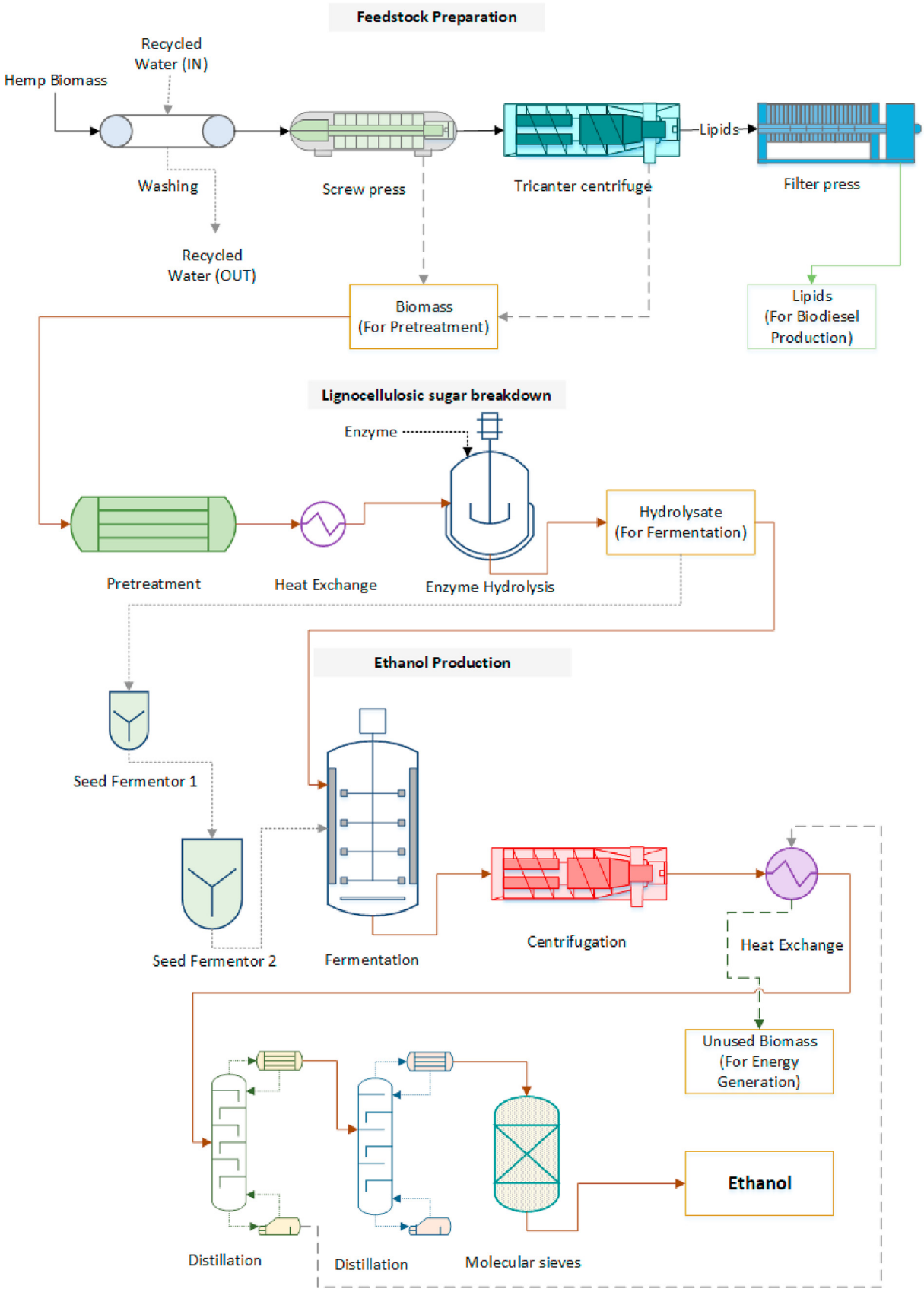


Fig. 1. Feedstock preparation, Sugar breakdown and ethanol production section comprising fermentation and ethanol purification.

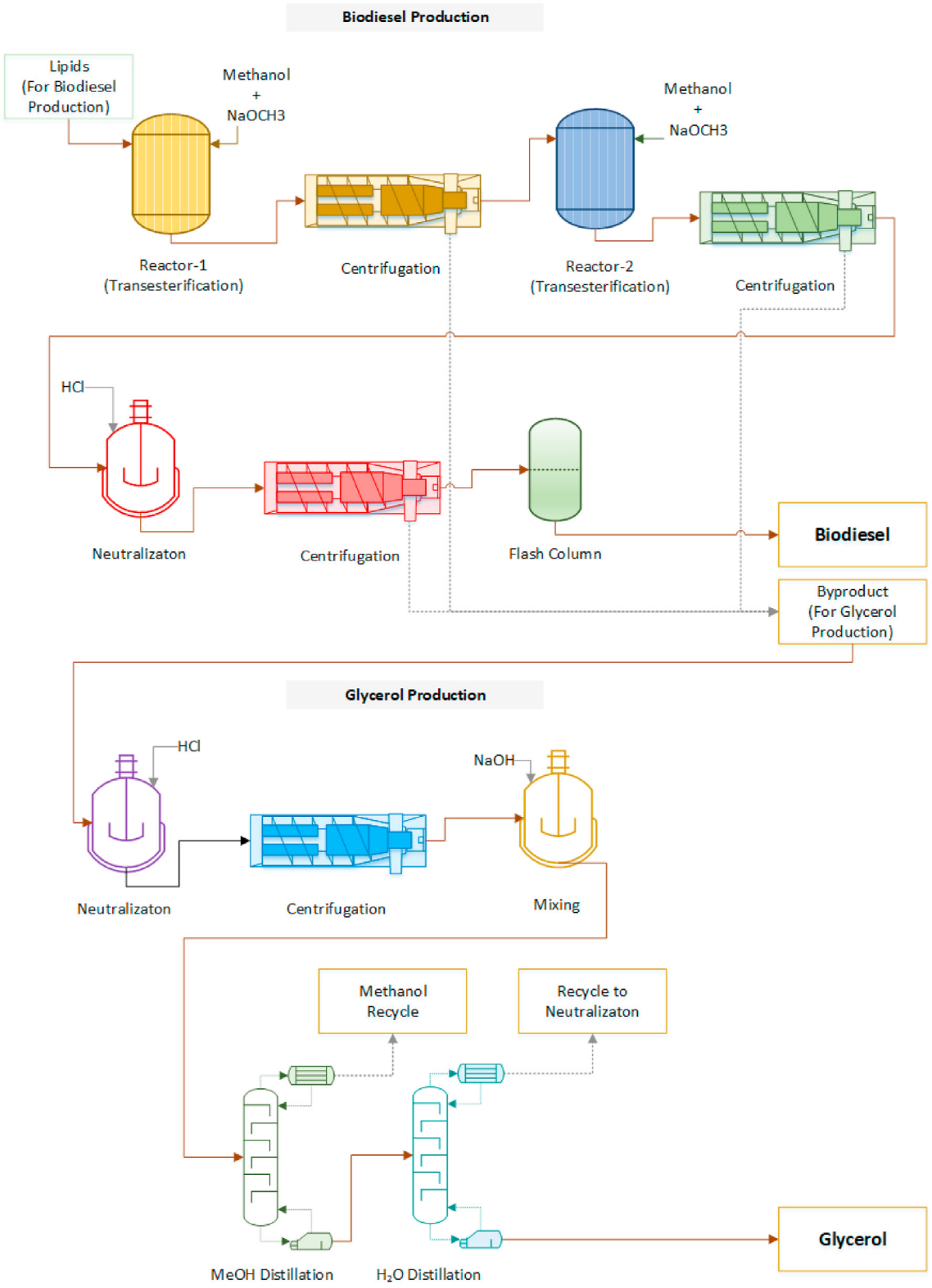


Fig. 2. Biodiesel production section – Transesterification and biodiesel purification.

using Cellic® Ctec2 enzyme (protein content: 76.3 mg/mL by bovine serum albumin (BSA) analysis) (Novozymes, North America, Inc., Franklinton, NC, USA) at 0.215 mL/g dry substrate basis. The conversion of cellulose to glucose and hemicellulose to xylose was set to 85 and 80% respectively (Wang et al., 2019). Following 72-h hydrolysis treatment, the hydrolysate, containing glucose and xylose, was harvested and stored, later to be fermented to bioethanol.

2.2.3. Ethanol production and purification

Fig. 1 details the fermentation and subsequent distillation of ethanol from the harvested hydrolysate. A hydrolysate sub-stream was directed to a two-stage seed fermentation system for onsite cultured yeast cells. The fermentation process was conducted at 32 °C, for 72 h (Table 1). The yeast culture consumes both C5 and C6 sugars (xylose and glucose) leading to the production of ethanol and carbon dioxide. Post-fermentation, the product stream containing ethanol, water, unused sugars, along with yeast and remnant biomass was centrifuged. The separated yeast biomass is treated with antibiotics and recycled for next inoculation batch (Huang et al., 2016). Analogous to the dry-grind ethanol procedure, separation and purification of ethanol was achieved via distillation and molecular sieving steps. The ethanol stream was preheated in a heat exchanger system, by recycling the bottom stream from the first stage-1 distillation column. Then, the stream was concentrated from 22 to 60% in stage-1 distillation and further refined to 90% in stage-2. The concentrated ethanol was then dried by passing through molecular sieves, resulting in 99.60% (Kwiatkowski et al., 2006) pure product.

2.2.4. Biodiesel production and purification

Lipids extracted during feedstock preparation (section 2.2.1) were transesterified with methanol to produce biodiesel or fatty acid methyl esters (FAME) and glycerol (Fig. 2). The reaction was catalyzed by sodium methoxide in a continuous stirred tank reactor operated at 60 °C. Following an hour of transesterification, the glycerol byproduct was collected via centrifugation and collected in a recovery unit. The FAMEs product stream undergoes second-stage transesterification to achieve maximum utilization of lipids and the second round of glycerol recovery. The biodiesel (FAMEs) fraction was directed down for further refining, wherein it was washed with hydrochloric acid and water. This step neutralizes the catalyst and converts any soap to free fatty acids. The unreacted methanol was recovered through vacuum evaporation, condensed, and recycled. The resulting final product stream contains 99% biodiesel.

2.2.5. Glycerol production

The byproduct streams of transesterification and neutralization processes contain glycerol and methoxide. The byproduct streams from both transesterification and downstream purification steps were treated with hydrochloric acid to convert methoxide to methanol. The unreacted HCl was converted to NaCl with NaOH. The glycerol-rich stream fraction was then purified through a two-step distillation process (Fig. 2). Here, the methanol and water components of the stream were recovered as top product and recycled, while the bottom product, with approximately 85% glycerol (Table 1), (Huang et al., 2016).

2.2.6. Energy production

The residual materials including lignin, complex sugars, and other leftover feedstock biomass from oil extraction, tricanter centrifugation, and ethanol production sections were utilized to produce steam and electricity. The combined residual stream with 50% moisture was sent to a boiler for steam generation. With a calculated 80% efficiency, the boiler generates flue gas to preheat the air and to burn the bagasse (Humbird et al., 2011). The multi-stage steam turbine generates both high- and low-pressure steam that can be used within the plant for heating purposes. The electricity generated was used to power the plant and the energy generated was incorporated as a coproduct in the economic analysis.

2.3. Economic analysis

The SuperPro Designer® performs detailed process economics using self-simulated process data including mass and energy balance, equipment size, and operating variable quantifications. The scaling law method was chosen to determine the purchased equipment cost (equation (1)) (Peters, 2003). All cost data was adjusted to the year 2020 using CEPCI index values. The base cost and size of the equipment data were obtained from other published literature (Haas et al., 2006; Klein-Marcuschamer et al., 2013; Kwiatkowski et al., 2006) and from the SuperPro Designer® database. Cost information on the hydrothermal reactor was based on a quotation from equipment suppliers. Lang factor method was then used to determine the total fixed capital cost (Lang, 1947). A lang factor value of 3 as suggested by other literature studies (Haas et al., 2006; Humbird et al., 2011; Kwiatkowski et al., 2006) was used to account for direct and indirect costs to calculate the fixed capital investment for the project. Total capital investment was calculated as the sum of fixed capital calculated using the Lang factor method and working capital, estimated as 5% of the fixed capital investment (Humbird et al., 2011).

$$New\ cost\ =\ Base\ cost\ x\ \left(\frac{New\ size}{Base\ size}\right)^{Scaling\ exponent} \quad (1)$$

Operating cost was calculated for the annual consumption of the operating variable using their unit cost data. All end product and coproduct prices were obtained from the lipid-producing sugarcane model. These numbers were chosen such that results can be compared. Table 2 details the operating variables, primary product, coproducts, and their respective cost data used for this project.

There is no available data on industrial hemp raw material cost for energy production. The hemp used for other purposes such as fiber processing was priced at $200/MT (Sumner, 2020). Compared to generic lignocellulosic feedstock costs for energy production, this price is high. This is because the targeted market for hemp feedstock includes low-volume high-value essential oils and food but not bioenergy. Nevertheless, a price drop on industrial hemp feedstock can be expected due to an increase in production to supply for energy production. Therefore, we assumed feedstock cost at $100/MT. Later, to understand the economic impact of feedstock price, a sensitivity analysis on feedstock price was performed. The unit price of other operating variables was either

Table 2
Operating parameters, end product and coproducts unit costs data utilized for SuperPro Designer® process simulation.

Item	Unit cost data
Operating parameters	
Std Power	$0.05/kW-h
Steam	$2.60/MT
Steam-High P	$17.00/MT
Cooling Water	$0.05/MT
Chilled Water	$0.40/MT
Ammonium sulfate	$0.08/kg
HCl	$0.10/kg
Hemp	$100.00/MT
Hydrolase	$11.40/kg
Methanol	$0.24/kg
NaOCH3	$3.07/kg
Water	$0.50/MT
Operator	$20.00/h
End product and Coproducts	
Biodiesel	$1.22/L
Ethanol	$0.62/L
Crude glycerol	$0.21/kg
Electricity	$0.05/kWh

obtained from the software's database or the lipid-producing sugarcane model published earlier (Huang et al., 2016).

To compute the breakeven unit production cost of industrial hemp biodiesel, first, the annual expenditure on capital was calculated for insurance, maintenance, and depreciation. Then, annual production cost was calculated as the sum of annual expenditure on capital and operating costs (Haas et al., 2006; Kwiatkowski et al., 2006). Then, bioethanol, glycerol, and energy coproduct revenue was deducted from annual production cost, to determine the biodiesel production cost. The breakeven unit production cost (UPC) for biodiesel was then computed as the ratio of biodiesel annual production cost to annual production volume.

2.4. Cost and sensitivity analysis

Since the lipid content in the current 19 m hemp biomass was low, we assumed prospective lipid compositions for this analysis. Three different biomass composition scenarios/test cases with 2, 5, and 10% lipids were developed (Fig. 3) using the composition data as detailed in the feedstock composition section. We assumed that carbohydrate fraction in the biomass was replaced by lipids. The distribution of carbohydrate replacement was 60 and 40% of glucan and xylan respectively; lignin and ash concentrations were unaltered. The economic analysis was performed for all 3 test cases, by characterizing feedstock hemp using the data mentioned in Fig. 3. Case 1 with 2% lipid concentration was considered as the base case. The observed economics of producing biodiesel with 2% lipid-containing industrial hemp are detailed in the following section. Furthermore, the economic implications to improving the biomass lipid content are also discussed using simulation results for Cases 2 and 3.

Sensitivity analysis was performed on a collection of critical parameters, to determine their economic impacts. The percent change in UPC to a 10% change in the parametric value was measured. Feedstock cost is a critical parameter for bulk chemical production. Hemp as a feedstock was assumed to be available at a higher price than other lignocellulosic biomass, including sugarcane. Therefore, the variations in UPC due to feedstock cost was analyzed, as previously mentioned. Furthermore, sensitivity was performed on other important factors, including operating days, coproduct revenue, and steam and labor costs.

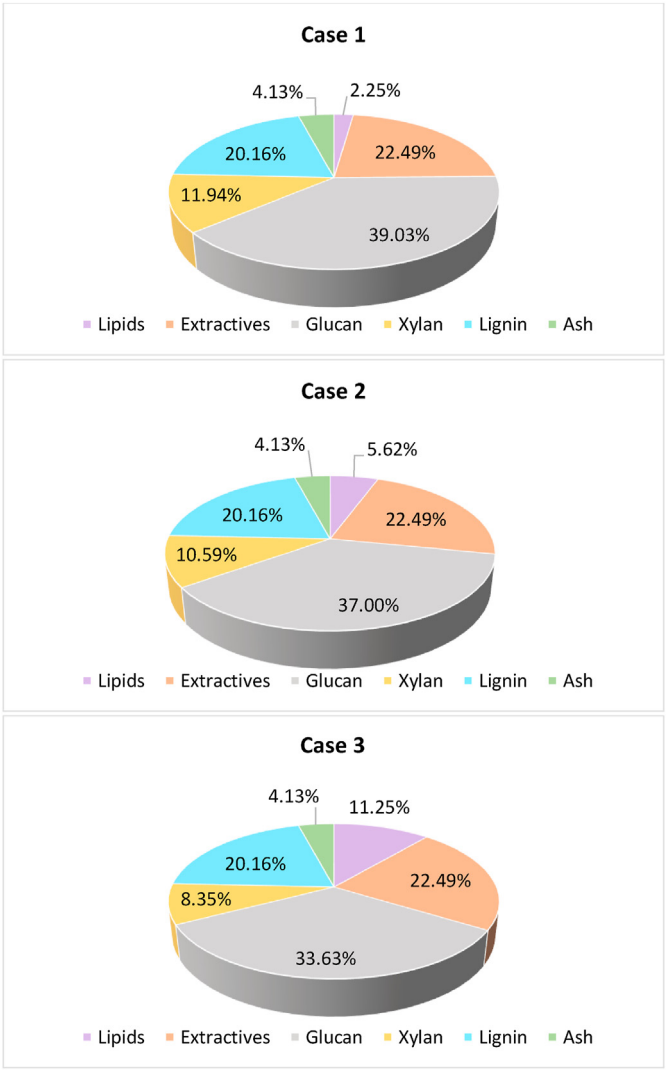


Fig. 3. Case wise composition of 19 m industrial hemp plant, used for SuperPro Designer® process simulation.*
*The current biomass contains negligible lipid content; therefore, scenarios are assumed to contain an increasing quantity of lipids.

3. Results and discussion

3.1. Annual biofuel and coproduct production

In this platform, annually, 3.95 million gallons (14.95 million liters) of biodiesel was produced from hemp containing 2% lipids. Additionally, 42.6 million gallons (161 million liters) of bioethanol, 0.30 million gallons (1.13 million liters) of glycerol, and 38 million kWh energy was produced (Fig. 4). For every metric ton of hemp biomass, 5.86 gallons (22.19 L) of biodiesel, 63.30 gallons (239.48 L) of ethanol, 0.44 gallons (1.66 L) of glycerol, and 56.50 kWh energy were generated. The biodiesel production increased by 150% and 404% as the lipid content of hemp was increased to 5% and 10%, respectively. Transesterification of lipid stream produces 2.75 and 4.80 million liters of glycerol coproduct at 5 and 10% lipid content. However, increasing the lipid content of the biomass will lead to a decrease in the production of bioethanol and electricity, due to reduction in carbohydrate content. In the 5% lipid content scenario, a 9% drop in bioethanol and 33% drop in electricity production was observed. Similarly, utilizing 10% lipid-containing hemp leads to a reduction in ethanol production by 20% and electricity by 38% from the base case scenario.

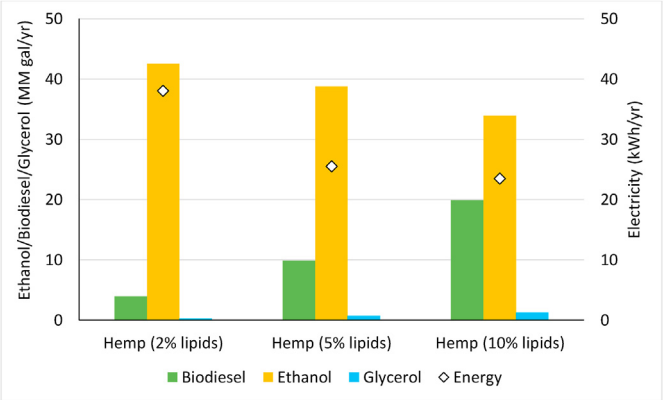


Fig. 4. Annual production of biofuels (Ethanol and Biodiesel) and coproducts (Glycerol and Energy) from varying lipid-containing hemp biomass.

3.2. Capital and operating cost

Table 3 summarizes the breakdown of estimated capital and operating costs for all three cases. The total investment on capital for the base case (2% lipid) was $464.41 million. Increasing lipid content leads to 4 and 9% decreases in capital investment, which are $445.30 and $434.52 million estimated at cases 2 and 3, respectively. The decrease in capital investment can be related to the lower carbohydrate contents in the feedstock, which were later utilized in ethanol production. Huang et al. (2016), reported a total capital investment of $173 million for lipid-cane containing 2% lipid. The significant difference in capital investment between hemp and lipid-cane can be understood by investigating the purchased equipment cost.

Equipment cost for ethanol and biodiesel coproduction using 2% lipid-containing hemp accounted for approximately $154.80 million. Pretreatment and enzyme hydrolysis equipment costs accounted for 65% of total equipment costs. Lipid-cane processing does not require these cost consuming sugar conversion processes, as extracted juice from the stem, containing sucrose was directly processed for ethanol production. Due to this advantage, lipid-cane bioenergy process consumed only $54.90 million on equipment costs. Furthermore, discounting pretreatment and enzyme hydrolysis equipment costs from hemp processing resulted in total purchased equipment cost similar to lipid-cane bioenergy process.

Annually, $101.88 million was spent as raw material cost annually, for producing 3.95 million gallons of hemp biodiesel (case 1). The total raw material cost was cut down by only $1.70 million when lipid content in hemp was improved from 2 to 10%. Feedstock hemp was the largest cost contributor, which is common for any fuel/chemical bulk production processes. The plant operating for 330 days at 85 MT biomass/hour, consumes $67.32 million in feedstock cost, accounting for 67% of total raw material cost and 38% of annual biodiesel production cost. The annual feedstock cost per gallon of soybean biodiesel and sugarcane bioethanol was $10.49 and $1.48, respectively (Huang et al., 2016). In case of lipid-cane, $0.23 and $0.33 were spent on feedstock per gallon of biodiesel and ethanol respectively. Hemp feedstock cost per gallon of biodiesel was estimated at $17.05 and $3.38 when hemp lipid content was at 2 and 10% respectively. Therefore, compared to soybean, the cost spent on feedstock per gallon of biodiesel was better in high lipid-containing hemp. Nevertheless, hemp cost consumption was still higher than lipid-cane. This was due to the feedstock unit cost difference between lipid-cane and hemp. Hemp was assumed to be available at $100/MT whereas the study performed with lipid-cane used feedstock cost at $35/MT. Furthermore, detailed sensitivity of product cost due to feedstock unit cost is described in a later section.

Enzyme consumption was another main contributor to the raw material costs, accounting for another $28 million (case 1). Upon increasing lipid content, the cost spent on enzyme was reduced to $27.10 and $25.60 million in cases 2 and 3 respectively. Increasing lipid content reduces cellulase enzyme consumption but increases methanol and methoxide requirements for transesterification. The costs of methanol consumption increased to $0.85 million and $1.71 million at cases 2 and 3 respectively. Similarly, methoxide consumption did cost $0.31 million at case 2 and $0.73 million at case 3. Utility costs contribute to 22% of the total operating cost at $33.20 million annually. Feedstock, enzymes, and utilities together account for 89% of the total operating cost. Of which, high-pressure steam, primarily used for hydrothermal pretreatment accounted for $14 million. Power requirements to operate the equipment added another $7 million to the total utility costs. The reduction in utility cost due to the cogeneration of steam and electricity is discussed in the following section.

3.3. Coproduct credit and breakeven UPC

The total coproduct credit was at approximately $104.73 million while consuming 2% lipid-containing hemp biomass. The major fraction of credit was obtained from ethanol production, which accounted for $102.53 million. Glycerol and electricity production add another $0.30 and $1.90 million. In case-2, ethanol coproduct credit decreases to $93.31 million and electricity to $1.29 million whereas, the transesterification byproduct, glycerol, earns $0.73 million. The total coproduct value drops to $95.33 million at case-2 and $84.06 million in case-3. Glycerol and energy production add $1.19 and $1.21 million respectively to and ethanol production at $81.65 million, when 10% lipid containing hemp was used as feedstock. The total coproduct credit per gallon of biodiesel for

Table 3
Capital and operating cost breakdown for biofuel production from hemp containing 2, 5 and 10% lipids.

Item	Case-1 (2% Lipid)	Case-2 (5% Lipid)	Case-3 (10% Lipid)
Raw Materials			
Hemp	67.32	67.32	67.32
Hydrolase	28.00	27.10	25.60
Methanol	0.34	0.85	1.71
$NaOCH_3$	0.13	0.31	0.73
Octane	3.37	3.07	2.98
Water	1.63	0.84	0.81
Total Raw materials cost	100.87	99.58	99.22
Utilities	33.19	30.93	28.86
Operating labor	12.14	12.14	12.14
Non-operating labor	1.82	1.82	1.82
Waste Treatment/Disposal	1.84	1.85	1.85
Total Operating Cost	149.86	146.32	143.89
Equipment purchase cost	154.80	148.14	144.84
Fixed capital investment	464.41	445.29	434.52
Working capital	69.66	66.79	65.18
Total investment	534.07	512.09	499.70
Amortized Capital	27.86	26.72	26.07
Annual Production Cost	177.73	173.04	169.96
Coproduct credit			
Ethanol	102.53	93.31	81.65
Glycerol	0.30	0.73	1.19
Electricity	1.90	1.29	1.21
Total Coproduct credit	104.73	95.33	84.06

soybean and lipid-cane (10% lipid) was $7.20 and $1.15. Compared to soybean, 10% lipid-containing hemp provided 41% lower credit but nearly 2.7 times more than lipid-cane at $4.20/gallon of biodiesel.

The biodiesel breakeven UPC with 2% lipid containing hemp was estimated at $18.50/gallon. Increasing the lipid content to 5% improves the UPC by 57% to $7.87/gallon. Consuming hemp containing 10% lipids will benefit low biodiesel UPC at $4.31/gallon, nearly 77% less than case − 1. Although ethanol production was decreased on improving lipid content in biomass, the total economic value was increased. This is due to the high economic value of biodiesel as the unit price of biodiesel is more than ethanol. Fig. 5 compares biodiesel UPC between hemp (Cases 2 and 3), soybean, and lipid-cane. At $7.87/gal, the biodiesel produced from 5% lipid-containing hemp was expensive than soybean by 89%. Similarly, the hemp biodiesel was priced 144% expensive than lipid-cane biodiesel. However, the economic value of hemp biodiesel was on par with soybean diesel when its lipid content was increased to 10%. Nevertheless, if hemp is available at a better price, hemp biodiesel can be less expensive than soybean biodiesel.

3.4. Sensitivity analysis

Fig. 6 illustrates the results of sensitivity analysis performed on key processes and cost parameters to determine their effects on biodiesel UPC. Among the process parameters, the UPC was most sensitive to operating days, followed by coproduct revenue. Operating the plant at 297 days results in $3.59/gal biodiesel UPC, which was the lowest recorded. This result indicates the plant can operate at high efficiency and save time; therefore, consumption of operating cost variables that depend on the time factor was reduced. Similarly, a 10% increase in operating days leads to an increase in UPC by 16%. On improving coproduct value or selling price by 10%, a 9.78% reduction in biodiesel UPC can be realized. Improving coproduct value leads to increased total credits and therefore drops the biodiesel production cost and in turn biodiesel UPC. Feedstock cost was the third major cost sensitive factor. A 10% decrease in feedstock cost can lead to 7.83% reduction in UPC. The biodiesel cost at this point was $3.98/gal, which is 4.27% less than soybean biodiesel cost. Furthermore, since feedstock cost was assumed at $100/MT, a 50% reduction reflects UPC at $2.62/gal, which is in the range of lipid-cane biodiesel (10% lipid). This illustrates that significant cost benefits can be realized in future, once commercial production of 19 m industrial hemp plant is executed. The labor cost was not surprisingly a low sensitive factor, as it is common in bulk production. An average of 1.58% change in biodiesel UPC was observed for a 10% change in labor cost. The steam cost was another low sensitive factor showing only 1.53% observed change in UPC. Although, utilizing the steam produced during power generation can lead to another 2% decrease in utility cost. Therefore, a total of 3.5% in UPC reduction is possible upon a 10% reduction in steam cost and recycling steam from the turbine.

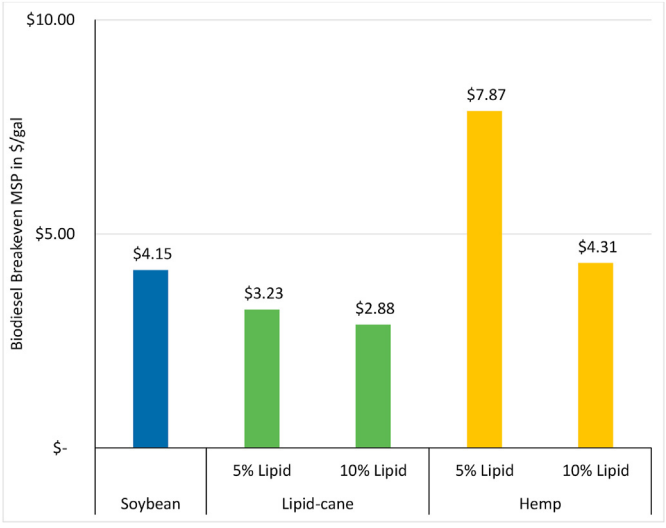


Fig. 5. Comparison of breakeven MSP of biodiesel produced from between Soybean, Lipid-cane and Hemp.

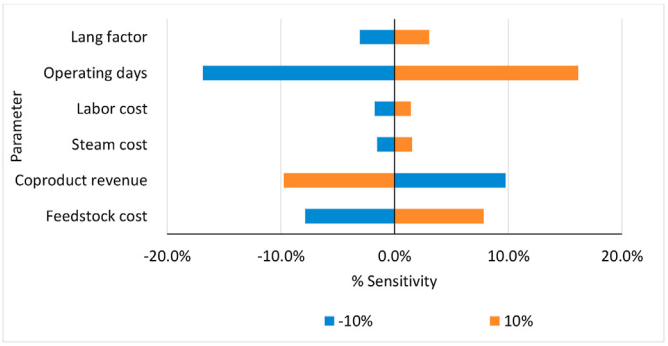


Fig. 6. Sensitivity analysis of hemp biodiesel MSP to cost and process parameters.

3.5. Biofuel production per land area

Fig. 7 compares biofuel production per hectare of the agricultural land area when cultivated with soybean, sugarcane, and hemp bioenergy crops. Sugarcane can yield approximately 2600 gallons of ethanol, and soybean yields 130 gallons of biodiesel per hectare of cultivation land (Huang et al., 2016). The total biofuels produced per hectare of agricultural land with 19 m hemp was between 437.80 and 455.82 gallons. The 2% lipid-containing hemp can yield 39.47 gallons of biodiesel and 398.32 gallons of bioethanol. Improving lipid content to 5 and 10% improves biodiesel production to 98.68 and 197.36 gallons/ha. Concurrently, bioethanol production reduces to 351.70 gal/ha (5% lipid hemp) and 258.46 gal/ha (10% lipid hemp). Hence, based on biofuel yield per agricultural land area as well as economic value, hemp biomass is favorable than soybean.

4. Conclusions

In this study, the hemp biofuel production process was simulated, and a detailed technoeconomic analysis was performed using

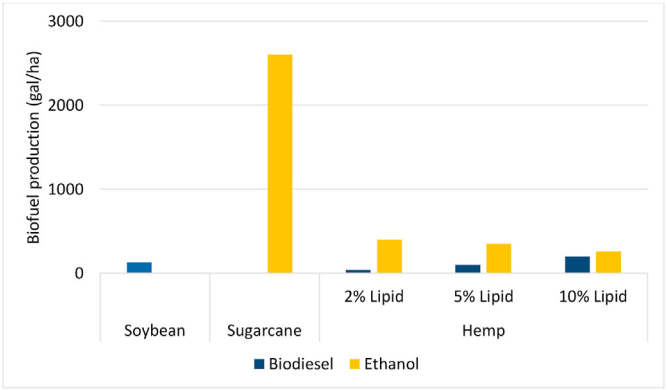


Fig. 7. Biofuel production per hectare of Soybean, Sugarcane and Hemp cultivation.

SuperPro Designer®. Industrial hemp biomass variety 19 m was utilized to produce biodiesel. Between 3.95 and 19.91 million gallons of biodiesel can be produced when lipid content in the biomass ranged between 2 and 10%. At least 42.59 gallon of bioethanol was produced with 2% lipid-containing hemp, which decreased by 9%–33.96 million gallons upon, increasing the lipid content up to 10%.

The UPC of biodiesel, produced from 19 m industrial hemp plant biomass with 10% lipids was at $4.31/gal, which is in the range of soybean biodiesel cost ($4.15/gal). Additionally, a hectare of 19 hemp (10% lipids) can produce nearly 67 gallons more biodiesel than soybean. Comparing the two 10% lipid-containing biomass i.e., 19 m hemp and lipid-cane, if 19 m hemp can be produced at $50/MT, hemp biodiesel will be cheaper than lipid-cane biodiesel, in addition to highest biofuels yield per hectare of agricultural land. The economic benefits of producing hemp biodiesel iterates the importance of understanding the lipid metabolism in plant cells. Furthermore, this study demonstrates the critical research need, to focus on improving lipid accumulation in vegetative tissue. Followingly, characterizing the obtained lipids will enhance optimizing its separation as well as determining the quality of end product. Overall, the technoeconomic study shows that hemp can be a promising bioenergy crop, producing biodiesel at a lower price than soybean in addition to ethanol production.

CRediT authorship contribution statement

Mothi Bharath Viswanathan: Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Ming-Hsun Cheng:** Investigation, Writing – original draft, Writing – review & editing. **Tom Elmo Clemente:** Resources, Supervision. **Ismail Dweikat:** Resources, Supervision. **Vijay Singh:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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