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ORIGINAL RESEARCH

Techno-economic feasibility analysis of engineered energycane-based biorefinery co-producing biodiesel and ethanol

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Abstract

High feedstock cost and low oil yields per unit of land from temperate oilseed crops limit the growth of commercial-scale biodiesel production. Recently, highly productive crops, such as sugarcane and energycane, have been engineered to accumulate triacylglycerides (TAGs) that allow the production of far more industrial vegetable oil than previously possible. A proof-of-concept suggests that biodiesel production from engineered energycane will be possible. However, before making efforts for scale-up, it is critical to understand the commercial feasibility and economic competitiveness of this process. This study performs techno-economic analysis of a unique biorefinery processing energycane to co-produce biodiesel and ethanol. Comprehensive process simulation models were developed for two scenarios: (i) biodiesel from TAGs and ethanol from fermentation of sugars in juice and (ii) biodiesel from TAGs and ethanol from fermentation of sugars in juice and hydrolysis of carbohydrates in bagasse. Based on the target levels, the analysis was performed for energycane containing 0%, 5%, and 7.7% TAGs (d.b.). The biodiesel from engineered energycane was found economically viable and competitive to soybean biodiesel. Although the capital investment is higher compared to the soybean biodiesel plant, the biodiesel production costs (\$0.66–\$0.9/L) were lower than soybean biodiesel (\$0.91/L). Biorefinery-scenario-1 processing energycane containing 7.7% TAG produces biodiesel with profitability (IRR 7.84) slightly lower than soybean biodiesel (IRR 8.3), but yields five times of biodiesel per unit land and is self-sustainable for energy requirements. The surplus electricity can displace fossil electricity and provide environmental benefits. Monte Carlo simulation indicated that biorefinery is profitable with a 29%–65% probability (NPV > 0) which is largely controlled by feedstock composition and biodiesel market price. It is important to note that energycane can be grown on the marginal rainfed lands in S.E. USA, where soybean would not be viable. Biodiesel from engineered energycane would therefore be complementary to soydiesel in the United States.

KEYWORDS
biodiesel, bioethanol, energycane, TAG, techno-economic, transgenic

1 | INTRODUCTION

Meeting increasing energy demands renewably and with reduced carbon emissions, and in an economically viable manner, is a major global challenge. The transportation sector is among the major consumers of energy worldwide. In the United States, the transportation sector accounts for about 30% (29.84 trillion M.J.; 95% of this derived from petroleum-based fuels) of total energy use and 28% (1854 Tg CO_2 equivalent) of anthropogenic greenhouse gas (GHG) emissions (EIA, 2020a; Fasahati et al., 2019). Biodiesel and cellulosic ethanol are two promising alternatives to petro-based liquid transportation fuels that can be produced from renewable feedstocks and lead to significant environmental benefits (Field et al., 2020; Jaiswal et al., 2017; Parajuli et al., 2020; Somerville et al., 2010).

Biodiesel, most commonly produced by transesterification of vegetable oil, gives comparable engine performance to that of petro-diesel but produces low life cycle net emissions (Huang, Long, & Singh, 2016; Naveenkumar & Baskar, 2020). Biodiesel production in the United States has increased from 516 million gallons in 2009 to 1724 million gallons in 2019. However, most commercial biodiesel production uses food crops as feedstock. In 2019, 57% of the total biodiesel in the United States was produced using soybean oil. Corn oil and Canola oil contributed another 24% of the total biodiesel production (EIA, 2020b). While algae are considered a potential feedstock and extensively investigated for biodiesel production, large-scale commercial production has yet to occur. Similarly, the United States is the largest producer of bioethanol in the world (15.8 billion gallons in 2019; 56% of global total), more than 90% of it is produced using corn as a feedstock. In addition to the challenges of the food versus fuel debate, the need for highly productive land and intensive agricultural inputs, the use of these conventional food crops for biofuel production provides challenges of capacity limitation in terms of total feedstock availability and supply. According to Huang, Long, Clemente et al. (2016) and Huang, Long, Singh (2016), due to the low amount of oil produced (0.36 and 0.61 metric ton/ha) per hectare of land for soybean, the use of the entire US soybean crop would provide <10% of the distillate fuel oil used in the United States. Uncertain price fluctuation of these food crops is another challenge in resilient production of these biofuels. Feedstock price directly influences the biofuel production cost, determining its marketing competitiveness. The use of feedstocks such as waste cooking oil and animal fat can reduce the biodiesel production costs; however, their production volumes are small (less than 5%; EIA, 2020b; Huang, Long, & Singh, 2016). The demand for plant-based lipids for food and fuel is expected to double in the next 15 years, which necessitates the need for the identification of new feedstocks with high production yields of oil per unit land.

Recently, the use of metabolic engineering and plant genetics to divert carbon flux from sucrose to triacylglycerides (TAGs) in highly productive biomass crops like sugarcane and sweet sorghum, has emerged as a promising strategy to boost oil yields per hectare (Huang, Long, Clemente, et al., 2016; James et al., 2010; Parajuli et al., 2020; Vanhercke et al., 2014, 2019). Using the approach of co-expression of three genes (WRI1, DGAT1 and OLEOSIN) involved in TAG production, Vanhercke et al. (2014) achieved more than 15% TAG (of dry weight, dw) accumulation in tobacco. Using a similar multigene engineering approach, Parajuli et al. (2020) reported the TAG accumulation of 4.3% (% dw) in the stems and 8% in leaves of the engineered sugarcane, which is 400 times the content in wildtype sugarcane. Theoretically, diverting all energy from sucrose into TAG accumulation could produce up to 20% lipids (% dw) in sugarcane, which along with the high annual dry matter productivity of up to 60 t/ha could provide as high as 15 times more oil per unit land compared to soybean (Kumar et al., 2018). Energycane is another such crop under investigation. Compared with conventional sugarcane, energycane is dedicated bioenergy feedstock rich in fiber, low in sucrose, and more persistent on marginal soils and yielding up to almost 100 t/ha dry matter (Duval et al., 2013; Kim & Day, 2011; Matsuoka et al., 2014; Salassi et al., 2014). Efforts are being made through the ROGUE (Renewable Oil Generated with Ultra-productive Energycane) project (funded by the US DOE) to bioengineer TAG accumulation in the leaves and stems of energycane. This opens the way to produce far more industrial vegetable oil per unit of land than previously possible, using land that is marginal or unused for food production (ROGUE, 2020). Processing of these crops for biofuel production could produce high quantities of sustainable biofuel to meet demand in the United States.

As these crops are at the proof-of-concept stage, only laboratory-scale studies have been performed to estimate the biofuel potential. A proof-of-concept is showing that biodiesel production from engineered energycane will be possible, but will require a high level of investment to move this from the laboratory and small-scale testing to commercial development and deployment. To determine whether such an effort will have practical and economic viability on a commercial scale, a comprehensive techno-economic analysis (TEA) is needed. Techno-economic analysis (TEA) is a tool commonly used to determine the economic feasibility of the early-stage processes (Sakdasri et al., 2018). Huang, Long, Clemente et al. (2016) and Huang, Long, Singh (2016) performed TEA of co-production of ethanol and biodiesel by processing engineered sugarcane (lipid-cane) containing different levels of TAGs (2%–20%) and found that biodiesel production cost from 20% lipid-cane was lower than soybean and production yields were 13 times higher per unit land. Kumar et al. (2018) made similar observations from TEA for the co-production of jet fuel and ethanol from lipid-cane. Although the capital investment for this biorefinery was relatively high, the jet fuel production costs were found competitive and the fuel yields per unit land were estimated 16 times compared to conventional oil crops (Kumar et al., 2018). Fasahati et al. (2019) conducted TEA of biorefinery processing of genetically modified lipid-producing sorghum and concluded that the minimum ethanol selling price from the co-production of ethanol and biodiesel was lower compared to the ethanol only process.

To understand the potential fuel yields and establish capital and operating cost profiles of the process, the objective of this work was to perform a techno-economic analysis for commercial-scale biorefinery processing engineered energycane to co-produce biodiesel and ethanol. The analysis was performed by developing process models of energycane-based biorefineries using SuperPro Designer (Intelligen, Inc.). The models were developed for two scenarios: (i) biorefinery producing biodiesel from TAGs and ethanol from sugars in juice only, where the bagasse is burnt to produce steam and electricity (scenario 1), (ii) biorefinery producing biodiesel from TAGs and ethanol from fermentation of sugars in juice and sugars from hydrolysis of structural carbohydrates in bagasse (scenario 2; Figure 1). Based on the preliminary studies and target oil yields, the analysis was performed for energycane containing 0%, 5%, and 7.7% TAGs (dry basis). The 0% case refers to the processing of wildtype energycane, or referred as "current energycane" in this manuscript. To establish the confidence in the new developed technologies, a comprehensive uncertainty analysis was performed using the Monte Carlo simulation method.

2 | MATERIALS AND METHODS

2.1 | Energycane composition

The composition of energycane for various scenarios is listed in Table 1. As the engineered energycane is in the development stage, its composition was estimated based on the non-engineered energycane composition and energy balance (Aragon et al., 2015). A similar approach was used in techno-economic studies on biodiesel and jet fuel production from engineered sugarcane (Huang, Long, Clemente, et al., 2016; Huang, Long, & Singh, 2016; Kumar et al., 2018). As the energy density of vegetable oil (37 kJ/kg) is approximately 250% that of sucrose (15.7 kJ/kg), it was assumed that 2.5 units of sucrose would be replaced by 1 unit of oil (Huang, Long, Clemente, et al., 2016; Huang, Long, & Singh, 2016). Energycane contains 22.5% soluble sugars (in juice) and 70.6% fiber on a dry mass basis (Aragon et al., 2015). As a first approximation, if all energy from the sucrose is diverted to triacylglycerides (TAG), energycane could accumulate up to 7.7% TAGs by weight in its stem (dry mass basis). The fiber composition was assumed the same as energycane bagasse containing 38.8% cellulose, 23.4% hemicellulose, 21.5% lignin, and 3.7% ash (Aragon et al., 2015).

2.2 | Process model development and simulations

Comprehensive process models for biorefineries with a processing capacity of 1,600,000 metric tons (MT)/year of energycane per year were developed using SuperPro Designer (Intelligen, Inc.). Process models were developed for six cases: two biorefinery scenarios, each processing energycane containing 0%, 5%, and 7.7% TAGs in the stem. Similar to the sugarcane refineries and previous lipid-cane-based biorefinery models, the operation period was assumed 200 days per year (Huang, Long, Clemente, et al., 2016; Huang, Long, & Singh, 2016; Kumar et al., 2018). The processing capacity of 1.6 million tons/year (8000 tons/day) is equivalent to an intermediate-size sugarcane processing facility (Huang, Long, & Singh, 2016). Feedstock handling, oil/sugar separation, and biodiesel production sections were common in both

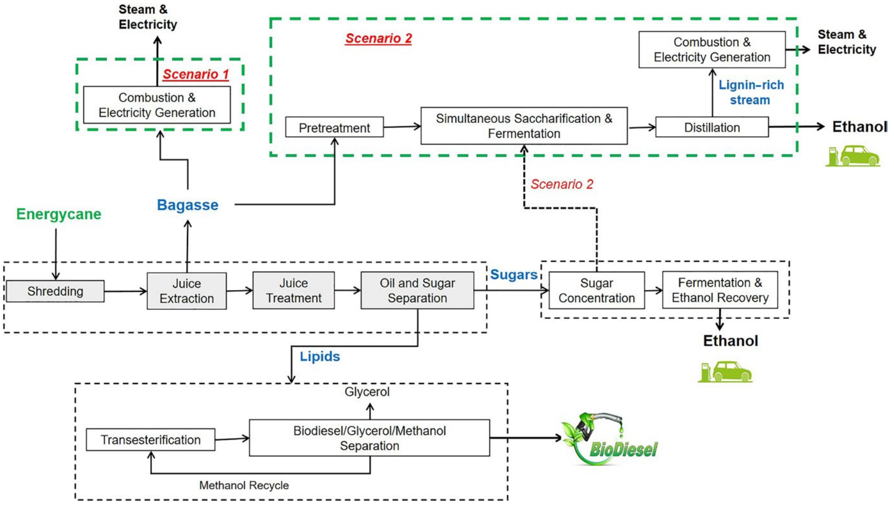


FIGURE 1 Schematic diagram of biorefineries producing ethanol and biodiesel from energycane for two scenarios: (i) bagasse burnt to produce steam and electricity and (ii) bagasse converted to cellulosic ethanol

TABLE 1 Composition of energycane used in process simulations (% wet basis; dry basis values in parentheses)[a]

	Energycane with 0% TAGs	Energycane with 5% TAGs	Energycane with 7.7% TAGs
Water	60	60	60
Sucrose	7.7 (19.3)	2.7 (6.8)	0
Lipids	0	2.0 (5.0)	3.1 (7.7)
Glucose	0.7 (1.7)	0.7 (1.7)	0.7 (1.7)
Fructose	0.6 (1.5)	0.6 (1.5)	0.6 (1.5)
Fiber	28.3 (70.6)	31.2 (78.1)	32.9 (82.2)
Ash[b]	2.8 (6.9)	2.8 (6.9)	2.8 (6.9)

[a] The composition of energy cane with 0% TAGs is based on Aragon et al. (2015).

[b] This ash does not include ash in the fiber.

scenarios. The bagasse obtained after sugar extraction was processed to produce steam and electricity in scenario 1 and processed to produce cellulosic ethanol in scenario 2. A brief description of the processes in both scenarios is given below and more details are provided in the supporting document of the manuscript.

2.2.1 | Scenario 1

Energycane is first shredded and cleaned using a magnetic separator. The cleaned biomass is conveyed to mill tandem consisting of a series of several crushing and juice extraction (using Imbibition water [process condensed water] at 60°C) units in a sequence Protease enzymes (0.5% concentration) were added during the extraction step to break down the proteins (including oleosin that surrounds the lipid bodies) and enhance extraction efficiency (Dickey et al., 2011; Huang, Long, & Singh, 2016; Majoni et al., 2011). The juice is further treated through a series of steps to remove impurities. Please refer to the supporting documents for details of the steps. The juice gets separated into three phases: lipids (floating on top), sugar solution (middle layer), and mud (remaining small fiber and soil). Lipid stream and sugar solution are then directed to the biodiesel and ethanol production sections, respectively. After juice extraction, solid residues obtained from the milling process, known as bagasse, are burnt to produce steam and electricity in scenario 1.

The clarified sugar solution is concentrated to about 20% sugar solution using multi-effect evaporators, cooled to 32°C, and transferred to fermenters. The sugar fermentation efficiency was assumed 95% (Table 2). The pure ethanol (>99% purity) from the fermented beer is recovered using a series of distillation columns and molecular sieves. Lipids were converted to biodiesel using a two-stage transesterification with methanol and using sodium methoxide as a catalyst. The process details were adapted from previous comprehensive studies and are provided in the supporting documents (Haas et al., 2006; Huang, Long, Clemente, et al., 2016; Huang, Long, & Singh, 2016). The transesterification efficiencies for the two stages were assumed 90% that lead to overall 99% conversion efficiency (90% conversion in the first and additional 9% in the second stage; Haas et al., 2006; Huang, Long, & Singh, 2016; Noureddini & Zhu, 1997). Both biodiesel and glycerol-rich streams are further purified through a series of steps. The unreacted methanol was recovered using vacuum evaporation, condensed, and recycled. Final biodiesel purity and glycerol purity are 99% and 80%, respectively (Huang, Long, & Singh, 2016).

TABLE 2 Major assumptions used in the energycane process model

Parameters	Values
Plant operation (MT/year, wet basis)	1,600,000
Extraction efficiency	
Sugar extraction in the mill tandem	96%
Lipid extraction in the mill tandem	90%
Sugar loss during purification	1%
Lipid loss during purification	2%
Conversion efficiency	
Hydrolysis—cellulose to glucose	85%
Hydrolysis—hemicellulose to sugar monomers	90%
Fermentation (hexose sugars)	95%
Fermentation (pentose sugars)	70%
Transesterification	99%
Co-production	
Boiler (65 bar pressure)	80%
Turbine	85%
End/intermediate products	
Anhydrous ethanol purity	99.7%
Biodiesel purity	99.2%
Crude glycerol	80%

Bagasse stream (about 50% moisture) containing structural carbohydrates and lignin is processed in the cogeneration section to produce steam and electricity. The process involves the use of a combustor and boiler for steam generation and turbogenerator for producing electricity. The process was modeled using the specifications, technical details, and equipment costs adapted from the process model of cellulosic ethanol developed by the National Renewable Energy Laboratory (NREL), where lignin-rich solids are burnt to produce steam and electricity (Humbird et al., 2011; Kazi et al., 2010; Kumar et al., 2018). The heating value of the bagasse stream was calculated based on the elemental composition (C, H, N, etc.) of the various fractions in the stream and combustor modules (model embedded). A high-pressure boiler was used to produce steam at 6.5 MPa. The turbogenerator uses a multistage turbine with two steam extraction ports (1.48 MPa and 268°C and 0.44 MPa and 152°C) and a condenser (Huang, Long, & Singh, 2016). The extraction fractions were adjusted based on the demand for steam in the plant. The remaining fraction of the steam is condensed at 10 kPa (45.8°C) to maximize electricity production (Huang, Long, & Singh, 2016; Kumar et al., 2018).

2.2.2 | Scenario 2

All process details for feedstock handling, juice extraction, lipid/sugar separation, and biodiesel production were same as in scenario 1. Instead of burning, the bagasse stream was processed to produce ethanol in this scenario. This consists of the additional steps of, milling (reduction), two-step pretreatment detailed below, simultaneous scarification, and co-fermentation (SSCoF), ethanol recovery, and cogeneration (from lignin-rich residues; Supporting File S3). The current process was modeled for a two-step chemical-free thermal pretreatment process. The process uses a sequential hot water pretreatment and disk milling, avoids the use of any chemical, and yields high hydrolysis efficiencies (Kim et al., 2016; Wang et al., 2018, 2019). The pretreatment process details and equipment costs were adapted from a previous process model developed for sugarcane bagasse (Cheng et al., 2019). The hot water pretreatment was modeled for 20% solids and at 180°C for 10 min. After exchanging heat with the incoming biomass slurry stream (please see supporting documents for details), the cooled output biomass stream is disk milled to increase the surface area of biomass (Cheng et al., 2019; Wang et al., 2018). Although the disk milling can be performed ahead of the hot water pretreatment also, the energy required for milling of already hydrotreated biomass could be up to 95% lower than processing raw biomass (Kim et al., 2016; Zhu et al., 2010). The electricity consumption in disk milling was assumed 0.035 kWh/kg wet biomass (20% solids; Cheng et al., 2019). After adjusting the solids back to 20% by adding process water (to compensate the moisture loss during disk mill), the pretreated stream was processed through a simultaneous saccharification and co-fermentation (SSCoF) process. The process was modeled assuming 15 FPU (filter paper units)/g cellulose enzyme loadings (Kumar & Murthy, 2011). The enzyme broth purchased from the market was assumed to contain 10% protein at 600 FPU/g protein activity (Kazi et al., 2010; Kumar & Murthy, 2011). Cellulose to glucose hydrolysis efficiency was assumed 90% (Table 2). The concentrated sugar solution (~20%) from evaporators is also added in the rector and ferment together with the sugars obtained after hydrolysis, using a xylose and glucose co-fermenting micro-organism (Figure 1). Fermentation efficiencies of 95% and 70% were assumed for glucose and xylose, respectively (Kim et al., 2013; Kumar & Murthy, 2011; Li et al., 2015). Similar to scenario 1, pure ethanol is recovered from beer using distillation columns and molecular sieves. The lignin-rich effluent obtained from the bottom of the beer column (1st distillation column) is passed through a pneumapress filter to separate into a solid stream (~45% moisture) and a liquid stream containing mostly water and soluble solids. The dissolved solids are concentrated by passing this liquid stream through multi-effect evaporators and the concentrated stream is mixed with the solid stream obtained from pneumapress filter to process in the cogeneration section for steam and electricity production. The condensate water stream from the evaporator is recycled back as process water. The design and details of the cogeneration section were similar to bagasse processing in scenario 1, accounting for the removal here of cellulose and hemicellulose.

2.2.3 | Soybean biodiesel model

To compare the process economics and profitability of an energycane-based biorefinery with conventional soybean-based biodiesel process, a previous soybean biodiesel model (Huang, Long, & Singh, 2016) was modified to update to the current year of analysis, material costs, and the scale of operation assumed for the energycane-based biorefinery. The model was set to 13.5 million gallons annual production capacity, to equal the capacity of energycane (7.7% TAGs) processing biorefinery. To meet the production target, 264,000 MT of soybean was processed annually (330 working days). Soybean composition was assumed the same (13% moisture, 18% lipids, 37% protein, 28% carbohydrates) as the previous study (Huang, Long, & Singh, 2016), but the price of soybean was updated using USDA/ERC database (USDA-ERS, 2018). All details of the unit processes simulated in the model can be found in Huang, Long, and Singh's study (2016).

2.3 | Economic analysis

Various reports were generated from the simulations of developed process models in this study, and the data were analyzed to determine process yields and economics. All economic calculations were performed for the Year 2019. The cost of the equipment used in the feedstock handling, juice extraction, lipid–sugar separation, biodiesel production, and cogeneration sections was calculated based on cost models of the previous lipid-cane biorefineries studies and NREL models (Huang, Long, Clemente, et al., 2016; Huang, Long, & Singh, 2016; Humbird et al., 2011; Kumar et al., 2018). The cost of highly specific equipment and enzymes used in the cellulosic ethanol production section was obtained from other comprehensive cellulosic ethanol modeling studies (Cheng et al., 2019; Humbird et al., 2011; Kazi et al., 2010; Kumar & Murthy, 2011). The exponential scaling equation (Equation 1) was used to calculate the cost of equipment for the size required in the modeled biorefineries. The exponential factor values for various equipment were used from the previous studies (Huang, Long, Clemente, et al., 2016; Humbird et al., 2011; Kumar & Murthy, 2011).

$$\text{New cost} = \text{Base cost} * \left(\frac{\text{new size}}{\text{base size}}\right)^{\text{exp}}. \qquad (1)$$

In addition to the equipment purchase cost, the calculations of direct fixed capital cost (DFC) consider several other direct (piping, installation, insulation, electrical, etc.) and indirect costs (design work, construction, and project contingencies). These costs were considered by calculating DFC using a Lang factor of 3.0, which is the standard value for the biorefinery techno-economic studies (Cheng et al., 2019; Haas et al., 2006; Huang, Long, Clemente, et al., 2016; Humbird et al., 2011; Kumar et al., 2018; Somavat et al., 2018). Working capital was assumed 5% of the DFC and added to DFC to calculate the total capital investment (TCI).

Operating costs consist of raw material, utilities, labor, and facility-related maintenance. The amounts of raw materials and utilities required, and quantities of biodiesel, bioethanol, and co-products were determined by the material and energy balances. The biomass (energycane) price was assumed $35/MT, similar to that assumed for lipid-cane (Huang, Long, Clemente, et al., 2016; Somavat et al., 2018). For the soybean biodiesel model, the soybean purchase cost was assumed $10.86/bu (10-year average; USDA-ERS, 2018). The costs of other chemicals and consumables were used from the recent studies or market values in the year 2019. The costs of electricity, process steam, and water were assumed $ 0.1/kWh, $12/MT, and $ 0.353/MT, respectively (Kumar et al., 2018; Somavat et al., 2018). Although cellulase enzymes can be produced in-house, considering the associated capital and logistics costs, on-site enzyme production was not considered in this model. Cellulase enzymes were assumed to be purchased externally at a cost of $0.517/kg of enzyme broth (10% protein; 600 FPU/g protein activity; Kazi et al., 2010; Kumar & Murthy, 2011). Labor costs were calculated assuming 50 employees with an average annual salary of $50,000 per employee (Huang, Long, Clemente, et al., 2016). All assumptions related to other operational costs (e.g., operating supplies, general and administrative, etc.) were kept consistent with the previous techno-economic studies on bioethanol and biodiesel production (Huang, Long, Clemente, et al., 2016; Kumar et al., 2018; Kurambhatti et al., 2019; Somavat et al., 2018). In addition to bioethanol and biodiesel, crude glycerol (80% purity) is produced as a co-product in the process. The selling price of crude glycerol was assumed $210/MT (Huang, Long, & Singh, 2016). Soybean meal, containing about 50% protein, is the major co-product in the soybean-based biodiesel process. The selling price of soybean meal was assumed $370/MT (10-year average; USDA-ERS, 2018).

In the case of a single main product, the unit production cost is normally calculated as the ratio of net operational costs (difference of total operational costs and co-product revenue) and the amount of product produced (Cheng et al., 2019; Haas et al., 2006; Kumar & Murthy, 2011; Kurambhatti et al., 2019). However, in the case of two main products, ethanol and biodiesel in the current case, different approaches have been used (Huang, Long, & Singh, 2016). The approach used here was to allocate the net operating costs between two main products based on their total marketing values, calculated based on the market selling price and quantity produced (Bonomi et al., 2011; Huang, Long, Clemente, et al., 2016; Huang, Long, & Singh, 2016). The selling price of biodiesel and bioethanol was assumed $3.79/gal and $1.92/gal, respectively, based on the historical average (2008–2017). The profitability of the energycane-based biorefinery and a soybean biodiesel plant was calculated in terms of internal rate of return (IRR) that accounts for integral economic parameters such as capital investment, revenue, depreciation, and time value of money, for assessing the economic performance of the processes for a given period (Huang, Long, & Singh, 2016; Kurambhatti et al., 2019; Somavat et al., 2018). The financial assumptions in estimating IRR were similar to those used in our previous techno-economic studies on other biofuel processes(Huang, Long, Clemente, et al., 2016; Kumar et al., 2018; Kurambhatti et al., 2019; Somavat et al., 2018), and are listed in Table 3 (Huang, Long, Clemente, et al., 2016; Kumar et al., 2018; Kurambhatti et al., 2019; Somavat et al., 2018).

2.4 | Uncertainty analysis: Monte Carlo simulation

Sensitivity analyses (one factor at a time) poses a limitation of not strictly representing real-life scenarios when more than one orthogonal parameters could vary simultaneously, making the analysis complicated. As discussed before, processes under evaluation are strongly affected by uncertainties that are associated with the process design and model development, or can be associated with raw material variability, volatile prices of products, investment cost, etc. To establish the confidence in the new developed technologies, possible uncertainties and the risks should be carefully analyzed. In this context, Monte Carlo simulation method was used as an intriguing method for solving stochastic system problems. This method provides approximate solutions to a variety of mathematical problems by performing statistical sampling experiments on a computer. To achieve this, a probabilistic model based on Monte Carlo method was developed with varying process parameters and various economic parameters. The model consists of equations that separately estimated the total revenue, and operational costs associated with the process to calculate NPVs. Normal and triangular distribution functions were used to describe the uncertainties of the model input parameters. The process model was developed on Microsoft excel. Random numbers were generated for each variable between two bounds decided based on the subject matter understanding and relevance for the project and probability distribution were generated to ascertain the possibility of uncertainty in NPV.

TABLE 3 Cost assumptions for the economic analysis of bio-refinery

Parameter	Value
Major raw materials	
Energycane ($/MT, wet basis)	35
Methanol ($/MT)	418
Protease enzymes ($/kg enzyme broth)	0.5
Cellulase enzymes ($/kg enzyme broth)	0.517
Hydrochloric acid ($/MT)	205
Phosphoric acid ($/MT)	420
Sodium hydroxide ($/MT)	410
Sodium methoxide ($/MT)	980
Lime ($/MT)	77
Utilities	
Process steam ($/MT)	12
Chilled water ($/MT)	0.4
Electricity ($/kWh)	0.1
Product and co-products	
Biodiesel ($/gal)	3.79
Ethanol ($/gal)	1.92
Crude Glycerol ($/MT)	210
Profitability analysis	
Project lifetime	20 years
Construction period	2 years
Salvage value of equipment	No value (0)
Distribution of capital investment	40% in 1st year and 60% in 2nd year
Depreciation life	MACRS 7-year depreciation schedule
Working capital	5% of fixed cost
Income tax	35%

Abbreviation: MARCS: Modified Accelerated Cost Recovery Systems.

The following variables are considered to be the most significant ones affecting the economic viability of the project: (i) cane lipids procurement price ($/kg), (ii) biodiesel price ($/ton), (iii) glycerol selling price ($/kg), (iv) filter cake price ($/ton), (v) lipids content in energy cane (%), (vi) selling price of ethanol ($/kg), and (vii) Selling price of electricity ($/kW-h). Other variables were kept constant during this analysis. Sensitivity bounds for the above variables followed normal distribution with mean ± standard deviations of all variables except lipid content of feedstock which followed triangular distribution (Table 4).

Based on scientific literature, communication with experts and commodity price data in the United States, we selected appropriate range for all the variables. A triangular distribution was assumed for cane lipid content so that uncertainties associated with preconceived lower and upper bounds can be evaluated. These input uncertainties will translate over NPV as corresponding output in the simulation model. The Monte Carlo simulation was conducted for a total of 10,000 iterations.

TABLE 4 Details of input parameters used in the Monte Carlo simulation

Parameters	Mean	Standard deviation	Distribution
Lipid energy cane price ($/ton)	35	3.33	Normal
Lipid content (%)	6.85	0.10	Triangular[a]
Biodiesel price ($/kg)	4.5	0.65	Normal
Ethanol selling price ($/kg)	2.3	0.4	Normal
Electricity selling price ($/kWh)	0.1	0.0083	Normal
Filter cake selling price ($/kg)	5	0.167	Normal
Glycerol selling price ($/ton)	210.5	17.5	Normal

[a] Most probable number for triangular distribution is 6.5% lipid content.

3 | RESULTS AND DISCUSSION

The process models were simulated to conduct a comprehensive material and energy balances for the biorefinery and to determine overall process yields, capital expenditures (CAPEX), operating expenses (OPEX), raw material, and utilities used in the plant.

3.1 | Process yields

Annual biodiesel production capacities were calculated 8.6 and 13.3 million gallons (32.4 and 50.3 million liters) for biorefineries processing engineered energycane with 5% and 7.7% TAG, respectively. There was no biodiesel production from the processing of the current energycane (non-engineered; 0% TAG). The biodiesel production capacity was the same in biorefinery scenarios 1 and 2. However, due to the ethanol production from both juice and bagasse, the total ethanol volumes produced were significantly higher for scenario 2. For energycane with 5% TAG, the total ethanol production in scenario 2 was 5.5 times higher than scenario 1 (57 vs. 10.4 million gallons). Figure 2 illustrates the biodiesel, ethanol, and surplus electricity yields per unit feedstock. For the energycane with maximum TAG content (7.7%), the biodiesel yield was estimated 31.3 L/MT of biomass (wet basis, 60% moisture). The maximum ethanol production (156.2 L/MT) was observed for the current energycane in scenario 2. The ethanol concentration decreases with an increase in TAG content in both scenarios because of the diversion of sugars to accumulate oil. Steam and electricity produced from the burning of bagasse or lignin-rich residues play a critical role in the modern sugarcane refineries and cellulosic ethanol plants. In the case of scenario 1, the steam and electricity produced from the burning of bagasse were sufficient to meet the biorefinery needs and surplus electricity (202.7 to 557.1 kWh/MT energycane) was assumed to be sold to the grid. Production of in-house steam and electricity makes the biorefinery self-sustainable and provides significant environmental advantages by avoiding the use of fossil-based energy and power. Electricity production increased with an increase in TAG content because of the higher percentage of fiber at high TAG contents. A similar trend was observed in the techno-economic studies about biodiesel and jet fuel production from lipidcane (Huang, Long, & Singh, 2016; Kumar et al., 2018). In the case of scenario 2, the steam and electricity produced from the burning of lignin-rich residue were not sufficient to meet the plant demands for all cases, that is, regardless of whether the energycane TAG content was (0%, 5%, and 7.7%). Steam, electricity, and cooling water production and requirements are discussed later in the manuscript.

Due to limited land resources, the challenge of low oil yields per unit of land from conventional oil crops is a major obstacle in the growth of the biodiesel industry. Relatively significantly high yields of energycane compared to conventional oil crops could potentially address this issue. Figure 3 compares the biofuel (biodiesel and bioethanol) yields per unit acre from energycane versus soybean. Biodiesel production from processing of energycane with 5% and 7.7% TAG was calculated 737 and 1142 L/acre, respectively, several folds higher compared to soybean (237 L/acre). In addition, up to 330–4906 L of ethanol/acre land was co-produced, depending on the TAG content and the scenario assumptions. More details are provided in the discussion section of the manuscript.

3.2 | Process economics

3.2.1 | Capital investment

Total capital investment includes direct fixed capital and working capital. As discussed in the previous section, DFC accounts for equipment purchase costs as well as associated direct and indirect costs. Table 5 gives an overview of overall process economics, including total capital investment and gross operational costs for biorefineries processing current

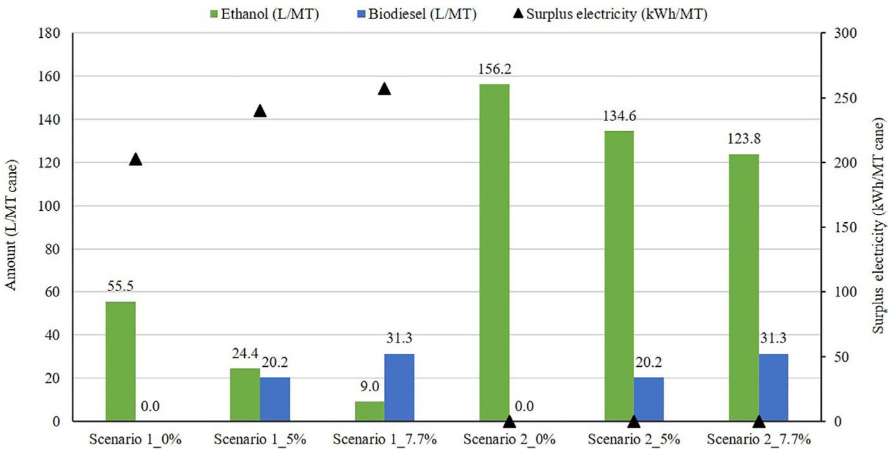


FIGURE 2 Process yields of biofuel (biodiesel and bioethanol) and surplus electricity per metric ton of energycane (wet basis; 60% moisture)

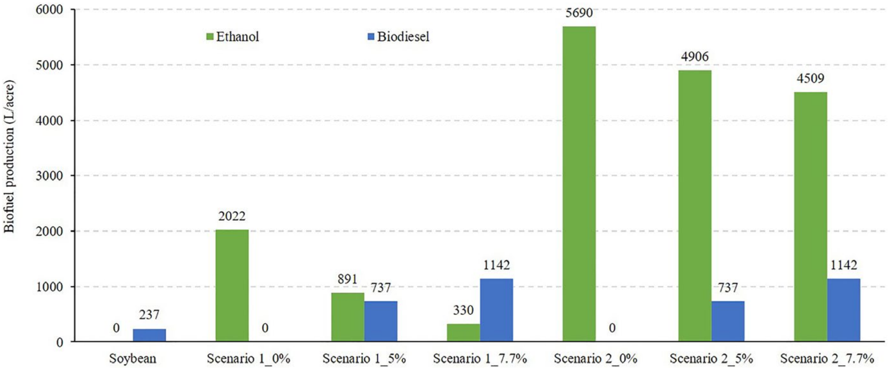


FIGURE 3 Biofuel productivity per unit of land from energycane biorefineries and soybean processing

TABLE 5 Overall process economics and biofuel yields of the biorefineries processing current and engineered energycane for two scenarios

	Scenario 1			Scenario 2			
TAG content (%)	**0%**	**5%**	**7.7%**	**0%**	**5%**	**7.7%**	**Soybean**
Total capital investment (million $)	220.5	238.7	244	364.4	393.5	406.6	59.1
Gross operating cost (million $)	79.5	81.5	82.1	124.1	127.1	129.5	120.84
Ethanol (million gal/year)	23.49	10.35	3.83	66.10	56.99	52.38	0
Biodiesel (million gal/year)	0.00	8.56	13.26	0	8.56	13.26	13.51

and engineered energycane for two scenarios. The capital cost for biorefinery processing engineered energycane with 7.7% TAG was only 10.7% and 11.6% higher than processing current energycane in scenarios 1 and 2, respectively. The capital investments for scenario 2 ($364.4–406.6 million) were more than 60% higher than in scenario 1 ($220.5–244 million) for both current and engineered energycane. This is because additional equipment is required to convert bagasse (lignocellulosic biomass) to ethanol. Several techno-economic studies have concluded that the lignocellulosic ethanol process is cost-intensive, due to the pretreatment reactor and cogeneration equipment, for steam and electricity generation (Cheng et al., 2019; Fasahati et al., 2019; Humbird et al., 2011; Kumar & Murthy, 2011).

Figure 4 shows the cost breakdown for biorefineries under the two scenarios. In scenario 1, the cogeneration section was the most expensive, contributing 63.5%–65.2% of the total equipment cost. The equipment cost and contribution of this section were higher for engineered energycane and increased with an increase in TAG content from 5% to 7.7%. This was due to greater fiber content in the higher TAG case, requiring larger equipment to process an increased amount of bagasse. The cogeneration section included the use of high-pressure, extraction-condensed turbogenerators, which are expensive, but highly efficient in producing electricity reducing the net operating costs of the biorefinery (Huang, Long, & Singh, 2016; Kumar et al., 2018). The design and cost data for the cogeneration system were adapted from the comprehensive studies conducted by the NREL, which could be considered close to actual commercial costs (Humbird et al., 2011). The contribution of cogeneration section in biorefinery scenario 2 was also significant (28%–29.2%) but lower relative to scenario 1. This results because, in scenario 2, only the lignin fraction of the bagasse is processed compared to the whole bagasse in scenario 1. In scenario 2, the structural carbohydrates, cellulose, and hemicellulose were converted to sugars and fermented to ethanol. Because of the additional equipment required for this pretreatment of the bagasse, the equipment cost for ethanol production section was more than six times ($69.2 to 71.6 million vs. 6.13 to $11 million) compared to scenario 1. In the case of biorefinery-scenario 2, only the cost of the hot water pretreatment reactor ranged from $29.2 to 31.7 million, accounting for about 25% of total refinery cost. The results are in agreement with other lignocellulosic ethanol studies (Cheng et al., 2019; Humbird et al., 2011). Due to the relatively large amount of sugars (both from juice and hydrolysis of bagasse carbohydrates), the cost of fermenters was also up to five times higher in biorefinery-scenario 2 compared to biorefinery-scenario 1. The equipment cost of fermenters ($11.4 to 12 million) in biorefinery-scenario 2 contributed from 8.8% to 10.4% of total equipment cost. For the same capacity of biodiesel production, the capital investment for energycane based biorefineries was several times higher compared to the soybean processing plant. This was mainly attributed to the high cost of biomass handling, in-house steam and electricity production, and ethanol production and recovery. These factors are discussed in detail in the discussion section of the manuscript.

3.2.2 | Operational costs

Annual operating costs, consisting of raw material, facility-dependent, labor, and utility costs, ranged from $79.5 to 129.5 million for the energycane-based biorefinery for different scenarios. Figure 5 illustrates the breakdown of gross operating costs for all cases. Raw material costs accounted for $60.5–85.4 million, contributing 65%–76% of total gross operating costs. Similar to other literature studies, feedstock cost was the major share (up to 93% in scenario 1) of total material cost. The share of feedstock cost in scenario 2 (66%–70%) was lower because of high cost of cellulase enzymes.

Although the actual cost of raw materials relatively higher in the case of scenario 2, its percentage contribution to the overall costs was smaller (65%–66% vs. 75%–76%). This was due to high overall operating costs for scenario 2 and relatively high utility costs and facility-dependent costs (maintenance, depreciation, etc.). Utility costs in the biorefinery-scenario 2 were higher due to a large amount of steam and electricity used in the biomass pretreatment and ethanol recovery process. Table 6 presents the utilities used in the various cases of both scenarios. In the case of scenario 1, the in-house steam and electricity production from the burning of bagasse were sufficient to meet the plant needs. In that case, the costs of steam and electricity used in biorefinery were set to zero and the main cost was chilled water. In biorefinery-scenario 2, after carbohydrate conversion to ethanol, only the lignin-rich fraction of bagasse was processed in the cogeneration section and the steam and electricity produced were less than the plant requirements, and costs associated with the purchase of additional steam and electricity were considered in the calculations of total operational costs. The total electricity requirement in the case of biorefinery-scenario 2 was 3.2–3.4 times higher than scenario 1. Disk milling requires significant electricity and accounted for more than 50% of the total electricity requirement in the plant. Similar results were reported by Cheng et al (2019) for sugarcane bagasse-based biorefinery using two steps hot water disk milling process.

3.2.3 | Production cost and profitability

Figure 6 presents the unit production cost of bioethanol and biodiesel, and compare these with the soybean-based biodiesel production cost and market prices. In all cases, the biodiesel production cost from energycane-based biorefineries

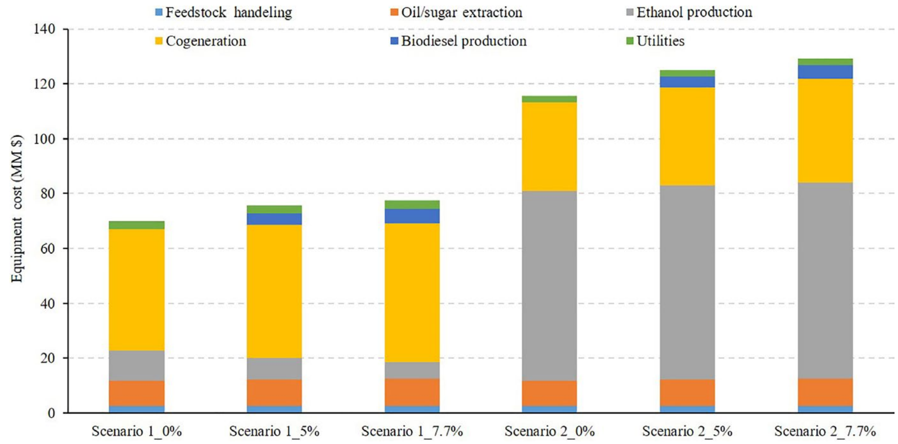


FIGURE 4 Equipment cost breakdown for the biorefineries processing current and engineered energycane for two scenarios

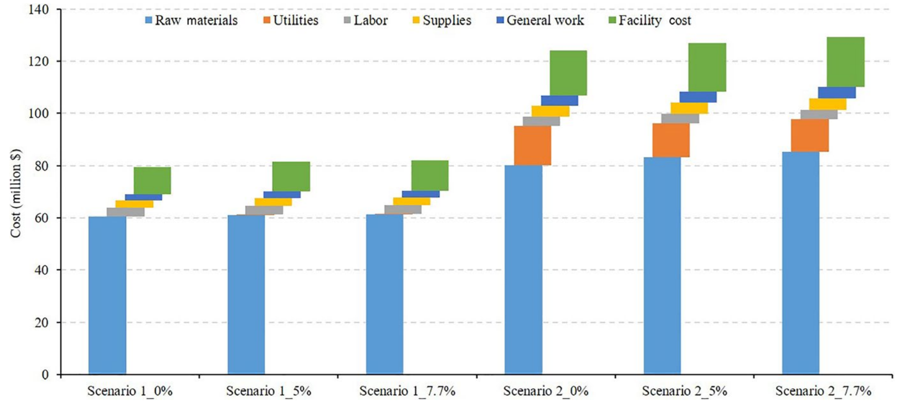


FIGURE 5 Operating cost breakdown for biorefineries processing current and engineered energycane for two scenarios

TABLE 6 Overall annual utilities used in the biorefineries processing current and engineered energycane for two scenarios

	Scenario 1			Scenario 2		
TAG content (%)	0%	5%	7.7%	0%	5%	7.7%
Electricity (MW)	51201	53127	53754	163371	175873	182356
Steam (MT)	473670	462184	468293	1828878	1865562	1884863
Steam (high pressure; MT)	0	1386	2092	155214	172184	182656
Cooling water (000 MT)	162249	184208	192906	116136	108193	103124
Chilled water (MT)	0	439864	677185	112600	557026	807659

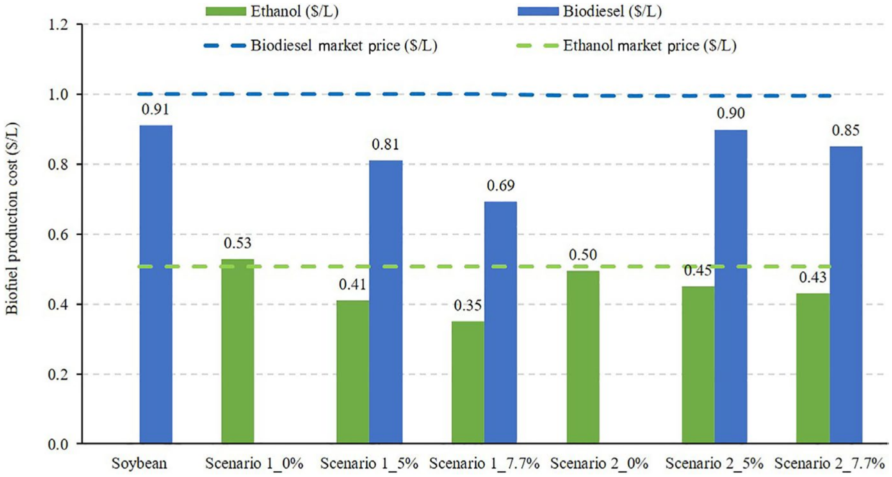


FIGURE 6 Biofuel unit production costs from energycane and soybean

was lower than soybean biodiesel. The minimum biodiesel production cost was observed in biorefinery-scenario 1 processing energycane with 7.7 TAG. In this case, the biodiesel production cost was 24% lower than soybean biodiesel cost. Although a large amount of bioethanol is produced in scenario 2, however, due to significantly higher operating costs, the biodiesel production costs were relatively higher compared to scenario 1. Detailed discussion about these observations is provided later in the discussion section of the manuscript.

It is important to note that although the biodiesel production cost was found relatively lower in energycane-based biorefineries compared to soybean biodiesel, the profitability was lower for energycane biorefineries. This is due to the significantly higher capital investment in energycane-based biorefineries compared to the soybean biodiesel plant. Figure 7 compares the IRR for various biorefinery scenarios and soybean-based biodiesel process. IRR accounts for several factors, including, income, capital investment, and the time value of money. In both biorefinery scenarios, the IRR values for engineered energycane processing cases (5% and 7.7% TAG) were higher compared to current energycane (0% TAG). This indicates that the development of engineered energycane crop can provide significant advantages compared to current (non-engineered) energycane by providing an opportunity to produce biodiesel and improving the process economics. The IRR of 7.84 for energycane containing 7.7 TAG in scenario 1 is relatively close to that for the soybean processing plant. This means that biorefinery-scenario 1 processing energycane containing 7.7 TAG produces biodiesel with a profitability close to soybean biodiesel, but yields 4.8 times of biodiesel per unit of land and is self-sustainable for energy requirements.

3.3 | Sensitivity analysis: Needs updated

As discussed in the last section, the plant profitability is dependent on the market price of the main products and co-products, which fluctuate dynamically with the markets. Similarly, raw material and process input costs fluctuate. Sensitivity analysis is important to understand the effect of those fluctuations on the process economics and profitability. Similarly, some of the process parameters, such as efficiencies and operating conditions, can significantly impact the process yields and it is critical to understand the effect of their variation on profitability. All sensitivity analyses were performed for biorefinery-scenario 1 processing energycane with 7.7% TAG and the results are presented in Figure 8. Feedstock price is considered usually the most critical parameter in all techno-economic studies of biorefineries (Huang, Long, & Singh, 2016; Humbird et al., 2011; Kazi et al., 2010; Kumar & Murthy, 2011) and was investigated here. Since the crop is in the development

FIGURE 7 Summary of internal rate of return (IRR) for energycane-based biorefineries and soybean biodiesel processing plant

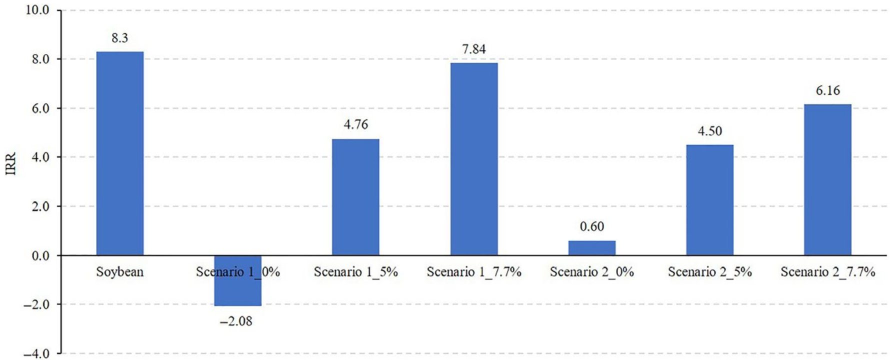
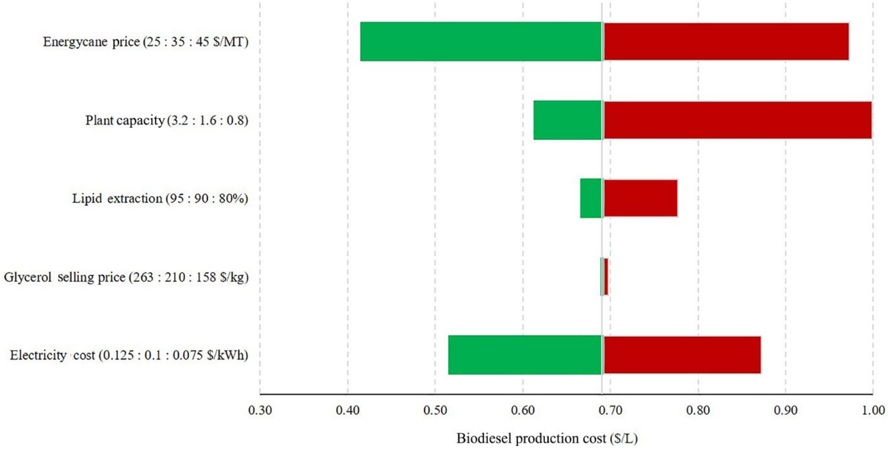


FIGURE 8 Sensitivity of biodiesel production cost to different parameters. The numbers in brackets in *Y*-axis are the potential low, base and high values of each parameter



stage, the actual price of the crop is uncertain. The base case simulations were performed assuming the price similar to lipid-cane ($35/MT). However, the price could be lower or higher depending on several factors, including biomass yield, oil content, and market demand. There is potential to achieve high biomass yields due to the synergistic effect of current research on photosynthesis improvements of crops and lipid accumulation and carbon assimilation (Huang, Long, & Singh, 2016; Vanhercke et al., 2014). Considering the crop in the developmental stage, a large variation ($25 to $45/MT) of feedstock price was investigated. A decrease in feedstock cost to $25/MT lowered the contribution of raw material in the total operating cost from 75% to 68% and decreased the biodiesel production cost to $0.41/L ($1.57/gal). The IRR under this condition was increased to 13.23. Similarly, increasing the feedstock price to $45/MT resulted in about a 20% increase in operational cost, and the biodiesel production cost was estimated $0.97/L ($3.68/gal). At these prices, the process is not profitable with an IRR value was close to zero (0.51). This high impact of biomass cost on the overall fuel production cost is in agreement with previous biofuel techno-economic studies (Fasahati et al., 2019; Huang, Long, & Singh, 2016; Kumar et al., 2018; Kumar & Murthy, 2011).

The size of the plant is another factor that significantly affects the economics and with an inverse relationship of plant size with unit fuel production cost (Humbird et al., 2011; Kumar et al., 2018). The biodiesel production cost in the current study was estimated to be $0.1/L (44.2% increase) and $0.61/L (11.5% decrease) by changing the plant capacity to half (0.8 million ton energycane annually) and double (3.2 million ton energycane annually) of base plant capacity, respectively. The production price decrease was relatively lower compared to the increase with the change in capacity. This could be explained by the fact that several equipment has higher-end capacity and after a certain point of increased capacity, the number of units (equipment) increase that results in higher capital investment and correspondingly high facility-dependent costs in the operational costs (Kumar et al., 2018). The capital cost was increased by 86% by doubling the plant capacity, whereas there was only 25% decrease in the investment for half capacity biorefinery compared to the base case. The lipid extraction efficiency is another uncertain parameter and its effect on biodiesel production cost was investigated (Figure 8). At 80% efficiency, the biodiesel production costs increased by about 12% ($2.94 vs. $2.62/gal biodiesel) compared to the 90% efficiency (base case). Revenue from the sale of co-products influence the process economics. Surplus electricity, being the major co-product, had a significant effect on biodiesel production cost (Figure 8). With a 25% increase in electricity selling price, the co-product revenue increased to $52.5 million and resulted in a biodiesel production cost of

$0.51/L, about 26% lower compared to the base case. These results are in agreement with the observations made by previous studies on engineered lipid-producing biomass (Huang, Long, & Singh, 2016; Kumar et al., 2018). Due to low quantities, glycerol selling price did not have any substantive effect on the biodiesel production cost.

3.4 | Uncertainty analysis

A Monte Carlo simulation was conducted in Microsoft excel to generate a distribution function of the likelihood of outcomes. Input uncertainties depend inherently on the raw material composition and other parameters which depend on the market forces causing the price fluctuations in the feedstock and different products (Arora & Singh, 2020). The ranges of the probability density functions of the energy cane procurement cost ($25–$45 per MT), biodiesel selling price ($2.33–$5.85 per gal [STP]), ethanol selling price ($1.15–$3.50 per gal [STP]), filter cake selling price ($4.5–$5.5 per MT), glycerol selling price ($158–$263 per MT) and lipid content in cane (6%–7.7%, dry basis) were evaluated to estimate NPV which is most reasonable acceptable indicator for financial risk assessment.

In Figure 9a, the area under the blue bars of normal distribution curve shows probability of NPV > 0, which indicates the probability of plant profitability. Considering total area under the curve, red zone occupies about 71%, which is indicative of NPV < 0. A +10% increase in biodiesel price range turns profitability probability of the proposed venture from 29% to ~50% (Figure 9b). This possibility is not far from reality in today's volatile market, especially when conventional soybean-oil-based biodiesel price is moving up due to consistent increase in soybean price in domestic and international market and it has been established that raw material price controls the fate of biodiesel production cost. Soybean oil is the primary feedstock for biodiesel in the United States and is the main driver of shifts in the biodiesel supply curve. The energy cane (feedstock) price range considered for uncertainty analysis is orthogonal to the commodity market volatility. Thus, lipid-cane-based biodiesel production would be more stable from input side.

4 | DISCUSSION

For the modeled biorefinery processing 1,600,000 MT engineered energycane, biodiesel production capacities were

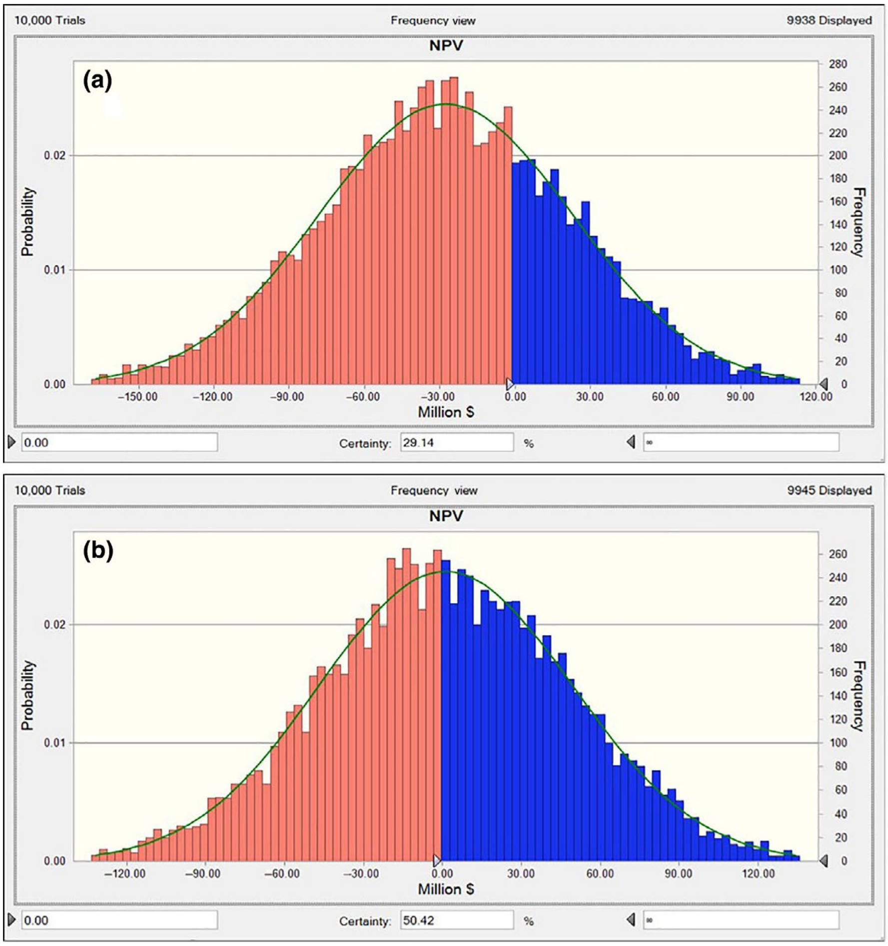


FIGURE 9 NPV probability distribution from Monte Carlo simulations for (a) parameters without considering hike in biodiesel price range (simulation range: $2.33–$5.85/gal(STP) and (b) parameters with 10% increase in minimum and maximum biodiesel selling price (simulation range: $2.50–$6.4/gal(STP). Area under the blue curve represents probability for NPV > 0 (desirable). Area under red curve represents probability of incurring losses, that is, NPV < 0

estimated 8.6 and 13.3 million gallons (32.4 and 50.3 million liters) annually, depending on whether an energycane TAG content of 5% and 7.7% was assumed, respectively. In scenario 2, which modeled ethanol production from fermentation of sugars in the juice and sugars obtained from hydrolysis of structural carbohydrates in bagasse, the ethanol production capacities were overall higher compared to scenario 1. The high yields of energycane versus soybean and even sugarcane are the major motivation for genetically engineering or transforming this crop to produce biodiesel, leading to significantly higher biofuel production per unit land area compared to conventional crops. Assuming 90 MT/ha of energycane yield (Aragon et al., 2015), the biodiesel production per unit land was found 737 and 1142 L/acre for energycane with 5% and 7.7% TAG, respectively. Crop yields of more than 100 MT/ha have also been reported for energycane (Salassi et al., 2014); hence, 90 MT/ha is a conservative estimate. Considering the biodiesel yield of 193.5 L/MT soybean and average soybean yield of 1.23 MT/acre (45 bu/acre; 10-year average; USDA, 2019), the total biodiesel production from one acre of land was estimated 237 L only. These would indicate that biodiesel productivity per unit land (737 L/acre) from engineered energycane with 5% TAGs was more than three times that of soybean, plus 891 and 4906 L of bioethanol in scenarios 1 and 2, respectively (Figure 3). In the case of energycane with 7.7% TAG, the biodiesel productivity per unit land area was almost five times that of soybean (Figure 3). Other than the production of two sustainable biofuels (biodiesel and ethanol), this energycane-based biorefinery provides an advantage of in-house steam and electricity generation from the bagasse (scenario 1) or lignin-rich residues (scenario 2), displacing fossil-based steam and electricity, which is not possible for conventional oil crops. This energy self-sustainability makes biodiesel production from energycane highly attractive compared to conventional feedstocks, such as soybean and Jatropha. In the case of the soybean biodiesel model (13.5 million gallons annual capacity), total electricity consumption was 22.6 million kWh, most of which is derived from fossil resources.

In terms of CAPEX, even for the same biodiesel production (13.5 million gallons), the capital investment for energycane-based biorefineries in scenarios 1 and 2 was about four and seven times than that of the soybean processing plant, respectively ($243.9 and $406.6 million vs. $59 million; Table 4). Similar observations were made by Huang, Long, and Singh (2016) and Fasahati et al. (2019) from TEA of biodiesel production from engineered lipid-producing sugarcane and sorghum, respectively. Huang, Long, Clemente et al. (2016) and Huang, Long, Singh (2016) reported that the capital investment for a lipid-cane based biodiesel refinery was 2.4 times that of soybean processing plant. These differences can be attributed to the additional equipment required for sugar concentrations and fermentation (in scenario 1), bagasse pretreatment and fermentation (scenario 2), and cogeneration (scenarios 1 and 2). Moreover, the equipment costs for front end operations are highly feedstock specific. Compared to soybean, a large amount of feedstock needs to be handled in the case of the energycane biorefinery leading to significantly higher front-end equipment costs (Diederichs et al., 2016; Huang, Long, & Singh, 2016; Kumar et al., 2018). The equipment cost difference from soybean plant (four times increase) in the current case (scenario 1; similar to lipid-cane) is higher than lipid-cane-based biorefinery producing biodiesel because of almost double fiber in energycane compared to sugarcane that resulted in larger cogeneration equipment and cost. Although the capital investment is significantly higher than for a soybean biodiesel plant, bioethanol and in-house steam and electricity production would replace fossil fuels, make the biodiesel production process more sustainable while providing significant environmental advantages.

Annual operating costs of the biorefinery were in the range of $79.5–129.5 million. In all the cases, the cost of raw materials caused more than 65% of the total operational cost. These observations are in agreement with other studies on biofuel production (Huang, Long, Clemente, et al., 2016; Huang, Long, & Singh, 2016; Kumar et al., 2018; Somavat et al., 2018). The energycane purchase cost was the major share (92%–93% in scenario 1 and 66%–70% in scenario 2) in the raw material costs. The biomass cost share was lower in the case of scenario 2 because of the high enzyme costs ($25.8 million) required for hydrolysis of cellulose, resulting in relatively higher total raw material costs ($80.2–85.4 vs. $60.5–61.2 million). The high cost of cellulase enzymes is a well-known challenge in the lignocellulosic biorefineries and one of the major bottlenecks in the economic feasibility of the lignocellulosic ethanol process (Kazi et al., 2010; Kumar & Murthy, 2011). Kumar and Murthy (2011) reported that cellulase enzymes can contribute up to 40% of total raw material costs. The contribution of enzyme cost in the current biorefinery-scenario 2 was up to 30% of total raw material costs. Similar to the observations made in other literature studies on biorefineries, facility-dependent costs (13%–15% of total operating cost) were observed as other significant economic driver in the process. Facility-dependent costs are proportional to the direct fixed capital. Due to higher capital investments in biorefinery-scenario 2, the facility-dependent costs were also higher and contributed $17.4–19.4 million in total operational costs compared to $10.5–11.6 million in scenario 1. Higher facility-dependent costs are commonly observed in lignocellulosic-based biorefineries.

Biodiesel production cost in all energycane-based biorefinery scenarios ($0.69–$0.90/L) was lower than biodiesel production cost from soybean ($0.91/L). Revenue from co-products plays a critical factor in unit production costs. Although the gross operational costs for soybean biodiesel plant ($120.8 million) were higher than most of the energycane-based biorefinery cases ($79.5–129.5 million), the revenue from co-products (mainly from soybean meal) resulted in low net operating costs and unit production cost of biodiesel. Similarly, the additional revenue from the surplus electricity offset some of the operational costs in the case of biorefinery-scenario 1 and resulted in a relatively lower unit production cost compared to scenario 2. Due to high steam and electricity demand, there was no surplus electricity in scenario 2. The co-product credit in biorefinery-scenario 1 ranged from $32.4 to 42.2 million, whereas it was less than $1 million in all cases of scenario 2. Due to the maximum amount of surplus electricity (257.2 kWh/MT energycane) in the case of processing energycane with 7.7% TAG in scenario 1 (Figure 2), the biodiesel production cost was the lowest. Even with the lower biodiesel production cost, the profitability (IRR) of energycane-based biorefineries was lower compared to the soybean biodiesel plant. It was mainly observed due to significantly higher capital investment in case of energycane-based biorefineries. To the same reason, the IRR values in scenario 2 are relatively lower mainly due to the high capital investment. The IRR values for biodiesel and ethanol co-production from engineered energycane (scenario 1: 4.76 to 7.84) are lower than values reported for biodiesel production from engineered sugarcane (13.7%–24%; Huang, Long, & Singh, 2016). This was mainly because Huang, Long, Clemente et al. (2016) and Huang, Long, Singh (2016) assumed selling prices of ethanol and biodiesel from the year 2013 ($1.22/liter and $0.62/L for biodiesel and ethanol, respectively), which are significantly higher compared to the current study ($1.00 and $0.51 for biodiesel and ethanol, respectively; an average of last 10 years). Due to higher selling prices of products, the total revenue was significantly higher leading to the higher IRR. Among all biorefinery scenarios, the profitability for energycane containing 7.7 TAG in scenario 1 (IRR of 7.84) is almost similar to the soybean processing plant.

4.1 | Conclusion, broader impact, and future directions

It can be concluded that the engineered energycane containing 7.7% TAG processed using technology-scenario 1 (biodiesel from TAGs, ethanol from fermentation of sugars in juice, and steam and electricity from burning of bagasse), a large amount of biodiesel can be produced per unit land (about five times that of soybean) at a production cost lower than the soybean biodiesel, and the biorefinery is self-sustainable for energy requirements and provides a similar profit to that of the soybean biodiesel plant. It should also be noted that the results in this study are limited to maximum TAG accumulation of 7.7%. As demonstrated by Huang, Long, and Singh (2016) and Arora and Singh (2020), higher lipid content in the feedstock would significantly influence area under the NPV probability distribution curve of uncertainty analysis and improve the chances of success. For energycane, accumulation of lipids beyond 7.7% does not seem to be a distant possibility. A closer look at the feedstock composition reveals that in foreseeable future, carbon in the form of glucose could be transformed into lipids through complex metabolic engineering research. Based on simulation results, we speculate that shifting of carbon from glucose to lipids could further improve plant profitability by 10%–15%, that is, probability of plant profitability can vary between 29% and 44%. With +10% increase in biodiesel price range, probability of NPV > 0 could reach as high as 65%. These results are even more attractive considering the fact that energycane would be growing on low-cost marginal land that could not support soybean production.

At the same time, it would be important to note that detailed field investigations and economic studies are needed to establish a cost profile of engineered energycane production considering the actual crop yields and agronomic perspectives. Similarly, further research is needed to achieve transformation of glucose to TAGs that can improve the biodiesel yields and process profitability. In addition, to be high yielding and the potential for production on marginal lands, energycane as feedstock can also provide ecosystem services. However, elucidating these broader impacts was not the objective of this study. Broader impacts related to carbon cycling, soil–microbiome interactions are being addressed by researchers looking at the sustainability aspects of these new crops.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article. Additional data are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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