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Techno-economic analysis of biodiesel and ethanol co-production from lipid-producing sugarcane

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Abstract: Biodiesel production from vegetable oils has progressively increased over the past two decades. However, due to the low amounts of oil produced per hectare from temperate oilseed crops (e.g. soybean), the opportunities for further increasing biodiesel production are limited. Genetically modified lipid-producing sugarcane (lipid-cane) possesses great potential for producing biodiesel as an alternative feedstock because of sugarcane's much higher productivity compared with soybean. In this study, techno-economic models were developed for biodiesel and ethanol coproduction from lipid-cane, assuming 2, 5, 10, or 20% lipid concentration in the harvested stem (dry mass basis). The models were compared with a conventional soybean biodiesel process model to assess lipid-cane's competiveness. In the lipid-cane process model, the extracted lipids were used to produce biodiesel by transesterification, and the remaining sugar was used to produce ethanol by fermentation. The results showed that the biodiesel production cost from lipid-cane decreased from \$0.89/L to \$0.59 /L as the lipid content increased from 2 to 20%; this cost was lower than that obtained for soybeans (\$1.08/L). The ethanol production costs from lipid-cane were between \$0.40/L and \$0.46/L. The internal rate of return (IRR) for the soybean biodiesel process was 15.0%, and the IRR for the lipid-cane process went from 13.7 to 24.0% as the lipid content increased from 2 to 20%. Because of its high productivity, lipid-cane with 20% lipid content can produce 6700 L of biodiesel from each hectare of land, whereas soybean can only produce approximately 500 L of biodiesel from each hectare of land. This would indicate that continued efforts to achieve lipid-producing sugarcane could make large-scale replacement of fossil-fuel-derived diesel without unrealistic demands on land area. © 2016 The Authors. *Biofuels, Bioproducts, Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Keywords: lipid; sugarcane; biodiesel; ethanol; techno-economic analysis; soybean

Introduction

The US objective to establish national energy independence and the worldwide efforts to reduce carbon emissions have spurred the development of biofuel technologies that are based on the use of crops and crop residues as feed stocks. Biodiesel is one of the most promising and simplest renewable biofuels to produce. It has been shown to give engine performance that is generally comparable to that of conventional diesel fuel while

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reducing the engine emissions of particulates, hydrocarbons, and carbon monoxide.[1,2] Hydro-treatment processes allow for its conversion to jet fuels.[3] With increased demand, US biodiesel production increased substantially from 32 million liters in 2001 to 5.1 billion liters in 2013.[4] The major US source of biodiesel has been and continues to be soybean.[5] Soybean has occupied about 33 million hectares in the USA, and is the second largest planted crop after corn, which occupies about 36 million hectares.[6] However, the amount of oil produced per hectare was small, between 0.36 and 0.61 MT/ha. In 2014, the USA consumed 155 million MT of distillate fuel oil.[7] Thus if the entire soybean crop were used for biodiesel production it would only provide one-tenth of national use and have to compete with food and feed uses of the oil.

The high production cost of biodiesel from vegetable oils is another barrier to its wide replacement of petroleum-based diesel. The biodiesel production cost in the USA is between $0.7 and $1.6/liter from 2007 to 2014.[8] This number is even higher than the US diesel retail prices between $0.5 and $1.2/liter in the same time period,[9] indicating the low marketing competitiveness of biodiesel. The main driver for the high production cost of biodiesel is the feedstock cost, which accounts for 80–90% of the total biodiesel production cost.[2,10,11]Animal fat and waste cooking oil provide opportunities to reduce the biodiesel production cost,[12,13] but their production volumes are also far below the demand for biodiesel production. With limited land resources, it is important to consider with the rapid progress of plant bioengineering to develop more productive crops that can accumulate oil and be grown on poorer soils and land that would not compete with the major US food and feed crops.[14]

Recently, metabolic engineering strategies have proven successful in generating and accumulating triacylglycerides (TAGs), the vegetable oil precursors of biodiesel, in plant vegetative tissues in place of non-structural carbohydrates (starch, sugars) in model plant species, *Arabidopsis* and tobacco.[15–19] By co-expression of three genes (WRINKLED1, DGAT, and Oleosins) involved in TAGs production, 19% of TAGs by dry weight were accumulated in a model plant, *tobacco.*[20, 21] By employing a similar strategy, our research team has successfully expressed the three lipid production genes, and accumulated 5% TAGs and 10% total fatty acids in engineered sugarcane in a lab-scale production.[22, 23] Field trials in northern Florida have been conducted to test the large-scale production of the engineered lipid-producing sugarcane (lipid-cane) (data not published). Based on the results from previous studies, the target of the lipid-cane is to accumulate a total of 20% lipid concentration in dry weight.

There are several important reasons that why sugarcane was chosen to be genetically modified to produce lipids over other crops. First, sugarcane is the most productive crop in terms of its ability to convert sunlight into chemical energy that can be stored in the plant through its effective use of C4 photo synthesis.The sugarcane yield of stem in the USA can be as high as 180 to 220 MT/ha (assuming 70% moisture),whereas the average soybean yield in the USA is only approximately 2.8 MT/ha.[24] Therefore, increasing the lipid concentration in sugarcane to a level similar to that of soybean can dramatically increase the lipid production per hectare of land area. Secondly, sugarcane is less demanding in terms of soil quality and fertilizer requirements and is more drought-tolerant than grain crops. Climatically, sugarcane is suited to the wet tropical and sub-tropical zones, which include the Gulf states, Puerto Rico, and Hawaii, where there are several million hectares of under-utilized land and sufficient rainfall of raise sugarcane without competing with food crops.[25] Thirdly, because of relatively low agricultural inputs and the large amount of residue that may be used to power the mill and fuel production system, fuels derived from sugarcane have a life-cycle greenhouse gas (GHG) emission that is less than one-eighth of that of fossil fuels.[14, 26] Finally and importantly, the remaining sucrose can be co-extracted with the TAGs and fermented to ethanol, which is another important renewable biofuel. Because this newly developed crop contains both lipids and sugar, it is an ideal dual-purpose biofuel crop: lipids are used to produce biodiesel, and the remaining sugars are used to produce ethanol. Before the adoption of this technology by farmers and processing plants, a techno-economic analysis is warranted to estimate the biodiesel and ethanol production costs from the lipid-producing sugarcane and to evaluate the overall economic feasibility of this crop.

The objective of this study was to techno-economically evaluate the use of lipid-cane for biodiesel and ethanol production. Based on the current and projected lipid concentration in lipid-cane, lipid concentrations at 2, 5, 10, and 20% were selected. The lipid-cane process was compared with a conventional soybean biodiesel (soy-biodiesel) process to assess lipid-cane's competitiveness, including the unit biofuel (i.e., biodiesel and ethanol) production costs and economic profitability. Sensitivity analyses were carried out to determine the variation in the biofuel unit production cost with the variables used in the economic analysis. Co-production of sugar is an important part of the annex sugarcane processing plants, however, this study focused on the energy (ethanol and biodiesel) productions from lipid-cane. Therefore, the sugar production from lipid-cane was not included.

Process descriptions

The flow diagrams of the proposed cane-and existing soy-based processes are shown in Figs 1 and 2, respectively. All process models were built using the SuperPro Designer software (8.5), which quantifies the processing characteristics, energy requirements, parameters of each piece of equipment, material flows, and efficiencies of conversion at each step. The input and output of the streams in the process were identified. In each unit operation, the relevant pieces of equipment were selected from the software database, and operational parameters were set such that the equipment efficiency and other conversion values agreed with those reported in the literature[2, 27–31] or those that are currently used in industrial practice. Some unit operations (e.g. mills, magnetic separator) were represented as component splitters due to the absence of the exact equipment in the Super Pro Designer database.

Lipid-cane process

The crush capacity for the lipid-cane process was selected to be 8000 metric ton (MT) stems per day. Because lipid-cane can be harvested during approximately 6 to 7 months of a year,[20, 39] 200 operating days were assumed for each year in the process model. Therefore, the annual feedstock requirement is 1 600 000 MT. This is an intermediate size for a sugarcane processing facility, according to a UNICA report.[28] If lipid-cane with 20% lipid content (dry basis) is selected as the feedstock, the process can produce approximately 96 million liters (25 million gallons) of biodiesel per year.

Composition

The composition of lipid-cane is one of the most important factors for the process design and economics. Lipid-

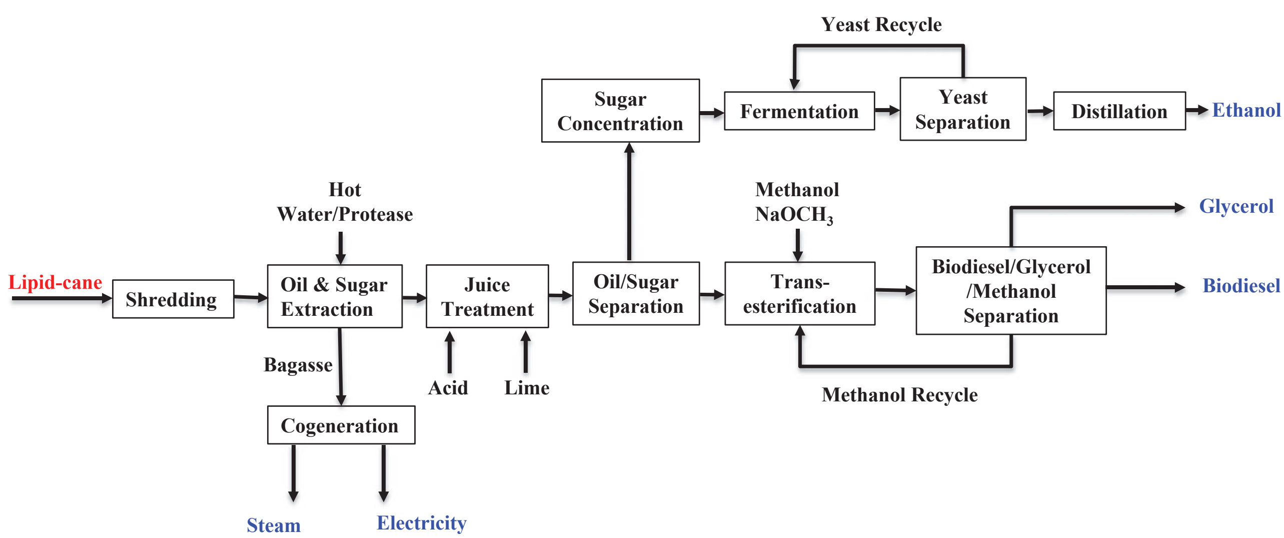

Figure 1. Flow diagram of the lipid-cane process.

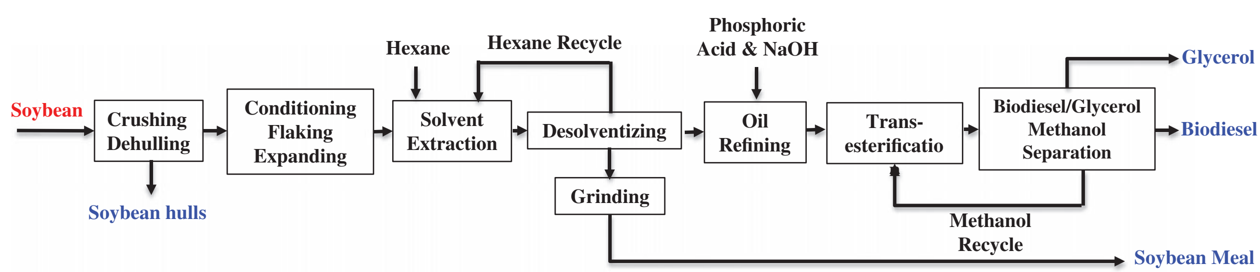

Figure 2. Flow diagram of soybean biodiesel process.

Table 1. Summary of sugarcane/lipid cane compositions used in simulation.

	Normal Sugarcane[a]	Lipid-cane with 2% lipids	Lipid-cane with 5% lipids	Lipid-cane with 10% lipids	Lipid-cane with 20% lipids
Water (%)	70.0[b]	70.0	70.0	70.0	70.0
Lipid (%)	0 (0)[c]	0.60 (2.0)	1.50 (5.0)	3.0 (10.0)	6.0 (20.0)
Sugar (%)	14.9 (49.7)	13.4 (44.7)	11.2 (37.2)	7.4 (24.7)	0 (0)
Fiber (%)	13.0 (43.3)	13.9 (46.3)	15.3 (50.8)	17.5 (58.3)	21.9 (73.0)
Ash (%)	0.60 (2.0)	0.60 (2.0)	0.60 (2.0)	0.60 (2.0)	0.60 (2.0)
Others (%)[d]	1.50 (5.0)	1.50 (5.0)	1.50 (5.0)	1.50 (5.0)	1.50 (5.0)

[a]The composition of normal sugarcane is as reported in a prior study.[30]
[b]Compositions are on a wet matter basis.
[c]Compositions in parentheses are on a dry matter basis.
[d]Other solids include organic acids, gums, and nitrogen compounds.

cane compositions with different lipid contents are listed in Table 1. For normal sugarcane with a negligible lipid content, the composition used is as reported in a prior study.[30] Currently, lipid-cane is not commercially available, which makes it difficult to quantify its exact composition. However, a potential composition can be proposed by an energy balance. The energy density of vegetable oil (37 kJ/kg) is approximately 2.5 times that of sucrose (15.7 kJ/kg); therefore, accumulating 1 kg of vegetable oil would require 2.5 kg of sucrose, to a first approximation. As the lipid content increases from 2 to 20% (dry matter basis), the sugar content is therefore assumed to decrease accordingly, from 49.7 to 0% (dry basis). It is assumed that the loss of the 1.5 kg of biomass (2.5 kg of lost sugar – 1.0 kg of oil) is compensated by structural carbohydrates (fiber), thereby making the total biomass yield of the lipid-cane the same as that of normal sugarcane. Thus, the fiber content of lipid-cane increases as the lipid content increases.

Lipid-cane receiving and preparation

Biodiesel and ethanol production from lipid-cane can be described as a five-stage process: lipid-cane reception and preparation, lipid and sugar extraction, biodiesel production, ethanol fermentation and distillation, and cogeneration (heat and power generation) (Fig. 1). The key parameters for the lipid-cane process model are listed in Table 2.

The first steps are essentially those used in current sugarcane operations coupled with ethanol production. Sugarcane stems are mechanically harvested and transported to the mill, where it is transferred to a conveyor leading to shredders. Magnetic separators are used on the shredded material to separate metal residues, mainly from

Table 2. Key parameters of the lipid-cane process model.

Parameter	Value
Amount of imbibition water	0.25 MT/TC[a]
Temperature of imbibition water	60 °C
Sugar extraction rate	96%
Lipid extraction rate	90%
Bagasse moisture content	50%
Amount of phosphoric acid addition	0.25 kg/TC
Amount of lime addition	1.0 kg/TC
Flocculant polymer addition	2.5 g/TC
Loss of sugar during purification	1%
Loss of lipids during purification	2%
Amount of methanol addition	6 times molar lipid content
Transesterification efficiency at 1st stage	90%
Transesterification efficiency at 2nd stage	90%
Fermentation sugar concentration	20%
Volume of added yeast solution	25% of the fermentation volume
Fermentation efficiency	90%
Fermentation time	10 hr
Biodiesel purity	99.2%
Ethanol purity	99.0%
Crude glycerol purity	80%
Boiler steam pressure	65 bar
Boiler efficiency	80%
Generator efficiency	85%
Steam pressure for pre-heating boiler-feed water	1.48 MPa
Steam pressure for the process	0.44 MPa

[a]TC: Tonne of Cane (wet basis).

the harvest machines, to prevent potential damage to the mill tandem, i.e. several crushing and extraction units in sequence. No washing is carried out on the lipid-cane prior to crushing due to the high sugar and lipid losses that would result from washing mechanically harvested lipid-cane prior to extraction.[30]

Lipid/sugar extraction

Shredders are used to cut the lipid-canestem to enhance the lipid and sugar extraction in the extraction step (Fig. 1). The juice extraction of the shredded lipid-cane follows the current well-established mechanical method (mill tandem) in sugarcane industry, with the assistance of enzymatic hydrolysis. During the extraction, process condensed water (imbibition water) at 60 °C is added at the final stage of the tandem to improve the lipid and sugar recovery. Protease enzyme is added at 0.5% concentration, to break down proteins, including oleosin that surrounds the lipid bodies.[32] Enzymes have been successfully applied to enhance aqueous extraction of lipids from different biomass materials.[33–35] The extracted juice contains water, lipids, sugar, and impurities such as fiber fragments, minerals, and soil particles. A rotary screen is used to remove the fiber fragments from the juice; these are returned to the mills for further recovery of lipids and sugar, and the juice is sent to the clarification process. Based on the information collected from sugarcane and soybean processing plants, it is assumed that 90% of the lipids and 96% of the sugar are extracted from the lipid-cane. A sensitivity analysis is conducted to evaluate the effect of the extraction efficiency on the process economic performance.

The extracted juice is piped to a temporary storage tank that provides a constant feed to the juice treatment process (Fig. 1). The juice is heated from 35 to 70 °C, followed by the addition of phosphoric acid to reduce the pH to 4.5 and followed by the addition of lime (calcium hydroxide) to increase the pH to 7 to remove impurities by forming calcium phosphate particles. A second heating is then applied to the juice to increase the temperature to 105 °C to remove dissolved air. Flocculant polymer is added to separate fine fiber fragments and soil particles from the juice in a settling tank. The juice then separates into three parts: lipids floating on the top, a sugar solution, and a mud debris of solid particles at the bottom of the settling tank. The mud is washed with fresh water to recover the remaining sugar using a rotary vacuum filter. The washed solution is recycled to the process prior to the settling tank, and the remaining material on the filter, termed filter cake, may be used as a component of animal feed or for composting.[27]

Biodiesel production by transesterification

Biodiesel production from the extracted lipids follows the process model developed in a previous study.[2] The process consists of transesterification, biodiesel purification, and glycerol recovery and purification (Fig. 1). Transesterification of the lipids with methanol, catalyzed by sodium methoxide, is conducted as a continuous reaction in a stirred tank reactor at 60 °C. The transesterification process continuously converts lipids and methanol to biodiesel and glycerol. Following a 1 h transesterification reaction, a continuous centrifuge is used to remove the glycerol-rich coproduct phase, which is sent to the glycerol recovery unit. The biodiesel stream, which also contains unreacted methanol and lipids, is fed to a second reaction tank, wheremore sodium methoxide and methanol are added. The second transesterification reaction is conducted for1 hr. A transesterification efficiency of 90% was assumed for each of the two transesterification-reactions, which resulted inan overall efficiency of 99% based on the lipid content.[2, 36] The unreacted methanol is recovered by vacuum evaporation followed by condensation for recycling.

The crude biodiesel stream is washed with hydrochloric acid and water to neutralize the catalyst (sodium methoxide) and convert any soap to free fatty acids, thereby reducing the fluid emulsifying tendencies. A continuous centrifuge is then used to separate the biodiesel from the aqueous phase. A vacuum drying process is applied to reduce the water content to 450 ppm. The crude glycerol stream is treated with the same process (hydrochloric acid and then caustic solution), and the processed crude glycerol has a purity of 80%.[2]

Ethanol production by fermentation

As in a modern sugarcane plant, the sugar solution is concentrated to 20% solute through a multiple effect evaporator (Fig. 1). The concentrated sugar solutionis cooled to 32 °C and fed into the fermenters, where a fermentation process with yeast is conducted. During fermentation, yeasts convert the sugars to ethanol and carbon dioxide. Cooling water is continuously provided to keep the fermentation temperature at 32 °C. After fermentation, the wine (water, ethanol, and yeast mix) is sent to centrifuges to separate the yeasts, which are treated with sulfuric acid solution to prevent bacterial contamination and recycled for use in further fermentation batches.

After removing the yeasts, the wine is sent to the distillation process to recover the ethanol. Before being sent to the distillation column, the wine is preheated in heat exchangers by the flow coming from the bottom of the distillation column. The first step in the ethanol recovery is the distillation column, which captures nearly all of the ethanol in the wine. The distillated ethanol solution contains almost an equal amount of water, so a second stage of distillation (rectifier column) is used. Upon completion of this second stage, the distillate is approximately 90% ethanol, and molecular sieves then remove further water to provide ethanol of 99% purity (*w/w*). The bottom flow from the distillation column, termed vinasse, contains water and nutrients including protein, fibers, and other unfermentable chemicals. This material can be utilized for both the irrigation and fertilization of the cane plantations that surround the ethanol production facility.[27]

Cogeneration system

Bagasse, a byproduct of the lipid-cane process, is burned to produce steam and generate electricity for the plant, with the excess sold to the grid for additional revenue. The cogeneration units comprise a combustor for burning bagasse, a boiler for generating steam, and a turbogenerator for converting thermal energy to electricity (Fig. 1). Such a cogeneration system using wet biomass has been included in aprocess model developed by the National Renewable Energy Laboratory (NREL).[31] The conceptual design and technical data in the NREL report were utilized for the simulation of the cogeneration unit in this study.

Bagasse with 50% moisture content is fed to the combustor to be burned to generate heat. The total heating value is calculated by the imbedded combustor-modules in the SuperPro Designer based on the material composition. The boiler efficiency was assumed to be 80%.[31] Flue gas leaving the boiler preheats the air required to burn the bagasse. A turbogenerator uses a multistage turbine with two steam extraction ports and a final condenser. The first extracted steam (1.48 MPa, 268 °C) is used to preheat the water before entering the boiler. The second steam is extracted at 0.44 MPa (152 °C) and is used in ethanol distillation, juice heating, and other processes. The rest of the steam is condensed at 10 kPa (45.8 °C) to maximally increase the electricity production.

Soy-biodiesel process

The soy-biodiesel process model is based on the model developed by the USDA ARS (Agricultural Research Service) research lab (unpublished). The capacity of the soy-biodiesel plant was set to 96 million liters (25 million gallons) biodiesel per year, which is the same as the capacity of the lipid-cane (20% lipid content) processing plant. To meet the target of 96 million-liters/yr for biodiesel production, the required mass of soybeans to be crushed is approximately 500 000 MT/yr. With an expected 330 working days per year, the required throughput is approximately 1500 MT/day. The soybeans contain 13% water, 18% lipids, 37% crude protein, 28% carbohydrates, and 4% ash.

The process includes two parts: (i) soybean crushing and oil refining and (ii) biodiesel production from refined oil (Fig. 2). The key parameters are provided in Table 3. After receiving the soybeans, the first step is to clean them to remove foreign materials, such as stems, pods, dirt, sand, and rocks, because such foreign materials reduce the oil and protein content and adversely affect oil quality. The cleaned soybeans are sent to a dehulling process to remove their hulls, which are toasted and grinded before being transported to a storage room. After the dehulling process, the cracked soybeans are subjected to conditioning, flaking, and expending processes, which help extract oil in the following extraction step. The soybean flakes are then sent to the oil extraction process, where hexane is used as a solvent to extract the oil. The oil extraction efficiency is assumed to be 95%, based on the data collected from a soybean plant. The hexane in the oil and the spent soybean flakes is then evaporated and recycled. The spent soybean flakes are ground to produce soybean meal and are sold as animal feed. The hexane-free soy oil is referred to as crude soy oil and is sent to the oil refining process.

Table 3. Key parameters of the soy-biodiesel process model.

Parameter	Value
Impurities removed by cleaning	0.3% of soybean
Soybean hull production	7% of soybean
Hexane usage during extraction	4.2 L/MT soybean
Solvent extraction temperature	60 °C
Lipid extraction rate	95%
Loss of lipids during purification	2%
Soybean hull moisture	12%
Soybean meal moisture	12%
Soybean meal protein content	50.0%
Amount of phosphoric acid addition	0.1% of lipids
Temperature of phosphoric treatment	70 °C
Amount of caustic soda addition	0.2% of lipids
Amount of washing water	15% of lipids
Temperature of washing water during purification	85 °C
Biodiesel purity	99.2%
Crude glycerol purity	80%

The soy oil refinery process consists of acid degumming with phosphoric acid followed by caustic treatment. Subsequently, hot water is used to wash the oil to further remove soaps and phosphates, and a disk-stack centrifuge is employed to separate the washed water from the soy oil. Then, a vacuum dryer is used to further reduce the water content in the oil to less than 20 ppm. The process of biodiesel production by transesterification is the same as the procedure described in the section *Biodiesel production by transesterification*

Economic analysis

Capital cost estimation

The mass and energy balance outputs from the processing models were used to evaluate the capital and operating costs. All currency used in the models is US dollars, adjusted to the year 2013. Equipment cost information was derived from previous studies,[2,30,31,37,38] quotes from equipment suppliers, and the SuperPro Software database. Becausethe equipment size required may be different than that available from different resources (e.g. literature, vendor quotes), an exponential scaling expression was used according to a previous study.[39]

$$New\ Cost = (Base\ cost)\left(\frac{New\ size}{Base\ size}\right)^{0.6} \quad (1)$$

The total fixed capital investment is calculated by the Lang factor, which is the ratio of the fixed capital investment to the total purchase cost of the equipment. The Lang factor is set to be 3.0, which is in agreement with other studies.[2, 31, 37] The total fixed capital investment cost includes the direct costs (e.g. installation, piping, warehouses) and indirect costs (e.g. proratable expenses, field expenses, construction fees, project contingencies). The working capital in this study is set to be 5% of the fixed capital investment.[31] The total capital investment is the sum of the fixed capital investment and the working capital investment.

Total operating costs

The total operating costs include both variable and fixed operating costs. Variable operating costs, which include raw material costs and co-product credits, are incurred only when the process is operating. The quantities of raw materials and co-products were determined by the material and energy balances. The unit price of materials and co-products were determined by their market values in the year 2013 (Table 4). All items are self-explanatory, with the exception of water. Some studies assumed that water was pumped from an underground saline source, so no cost was assigned to the water usage.[40] However, other studies assumed that water was purchased as a utility.[2] In this study, the water cost followed the latter case for conservative reasons, and a cost of $0.353/MT water was assumed. The total water consumption includes the process water

Table 4. Variable and fixed operating costs in this study.

Item	Cost (US$)
Raw materials and utilities	
Lipid-cane (70% m.c.)	0.035/kg[a]
Soybean (12% m.c.)	0.52/kg[a]
Methanol	0.547/kg[b]
Sodium methylate	2.93/kg[b]
Sodium hydroxide	0.41/kg[b]
Hexane	0.9/kg[b]
Hydrochloric acid	0.205/kg[b]
Protease	0.5/kg[b]
Lime	0.077/kg[b]
Electricity	0.065/KWh[b]
Steam	17/MT[b]
Natural gas	218/MT[b]
Water	0.353/MT[b]
Co-product credits	
Surplus electricity selling price	$0.065/kwh[b]
Crude glycerol (80% purity)	$0.21/kg[b]
Soybean meal	$0.48/kg[a]
Soybean hulls	$0.12/kg[b]
Fixed Operating Costs	
Labor costs	2,500,000[c]
Labor fringe benefits	40% of total labor costs
Operating supplies	20% of operating labor
Maintenance supplies	1% of fixed capital costs, annually
General and administrative	0.5% of fixed capital costs, annually
Property tax	0.1% of fixed capital costs, annually
Property Insurance	0.5% of fixed capital costs, annually

[a]The price of lipid-cane was assumed to be the same as that of sugarcane. The 2013 average prices of sugarcane, soybean, and soybean meal were from publically available data, such as USDA ERS.[52,54]
[b]Data are from different sources, including the ICIS chemical price report, other literature and industrial quotes.
[c]Assuming 50 employees with an average annual salary of $50 000 per employee.

(e.g. lipid and biodiesel washing, CO_2 gas scrubbing), the make-up water for the boilers, and the make-up water for the cooling towers. Fixed operating costs are generally incurred in full, regardless of whether the plant is producing at full capacity. These costs include labor and various overhead items. Many of the assumptions in the fixed operating costs followed those made by a prior study.[2]

Unit production costs and profitability analysis

The biofuel unit production cost was calculated based on the methods described in prior studies.[2, 39] For the soybean process, biodiesel is the main product, and soybean hulls, soybean meal, and crude glycerol are the co-products. For the lipid-cane process, biodiesel and ethanol are the main products, and surplus electricity and crude glycerol are the co-products. There are many approaches to obtaining the unit production costs when a process produces more than two main products, as is the case for the lipid-cane process in this study. One classic methodology is to proportionally allocate the net expenses (all expenses, less the co-product credits) to each of the main products with respect to their total marketing values.[30] The selection of allocation methodology affects the unit production cost of each main product, but it does not affect the overall process profitability when comparing the lipid-cane process with the soybean process. The internal rate of return (IRR) was evaluated using the parameters displayed in Table 5. The IRR gives the profit of the plant for a certain period by considering the time value of money. Sensitivity analyses were also performed for soybean and lipid-cane (10% lipid concentration)to evaluate the most influential parameters on the economic performance of the processes.

Table 5. Main parameters used for the economic profitability analysis (IRR).

Parameter	Value
Project lifetime	20 years
Salvage value of equipment	0
Construction and startup	2 years
1st year TCI allocation	40%
2nd year TCI allocation	60%
Depreciation life	MACRS 7-year depreciation schedule[a]
Income tax	35%
Working capital	5% of fixed capital costs
Biodiesel selling price	\$1.22/L[b]
Ethanol selling price	\$0.62/L[b]

[a]MARCS: Modified Accelerated Cost Recovery Systems.
[b]2013 average selling price from CARD Institute.[8]

Results and discussion

Capital costs of the process plants

A preliminary estimate of the total capital investment, including fixed capital and working capital, is summarized in Table 6. For a soy-biodiesel plant with a 96 million-liter capacity, the total capital investment is approximately \$84 million, where the majority of the investment comes from the feedstock handling and preparation and the oil extraction and purification sections. The capital investments of these two sections are consistent with the numbers in the previous report,[41] after being normalized by the plant capacity and money inflation. The total capital investment of a normal sugarcane processing plant at a capacity of 1.6 million MT/yr is \$159 million. Previous studies reported that the capital investment for sugarcane plants of a similar size are between \$140 and \$170 million,[29,30,42] which is comparable to the value found in this study. As the lipid content of the lipid-cane increases from 0 to 20%, the total capital investment increases from \$158 to \$199 million. The total capital investment of the lipid-cane plant is approximately 100–150% higher than that of the soy-biodiesel plant. This result makes sense because a higher amount of feedstock needs to be handled for the cane-based process, so equipment with a greater capacity is required. Of the equipment costs for the cane-based process, nearly half comes from the cogeneration system. Traditionally, sugarcane plants use low-pressure (2.2 MPa) steam and a turbo-generator that ensures only the energy self-sufficiency of the plants themselves. However, new green-field projects are currently adopting high-pressure, extraction-condensed turbo-generators, which allows for the production of significant surplus electricity.[28,42–44] A high-pressure cogeneration system at 6.5 MPa was selected in this study. A high-pressure co-generation system increases the total capital investment, but it also remarkably increases the boiler and turbo-generator efficiency, thereby producing more surplus electricity.

Biofuel and co-product production

One of the analyses conducted is to estimate the product yields from each metric ton (MT) of the lipid cane. Due to the compositional differences of the lipid-cane (Table 1), the final biofuel production yield will vary. For normal sugarcane, 88.4 liters of ethanol are produced from each

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Table 6. Project Total Capital Investment (million $) for the processes.

Sections	Soybean Biodiesel	Sugarcane 0% lipids	Lipid-cane 2% lipids	Lipid-cane 5% lipids	Lipid-cane 10% lipids	Lipid-cane 20% lipids
Feedstock handling	8.5	2.5	2.5	2.5	2.5	2.5
Oil/sugar extraction/purification	9.1	7.8	8.2	8.4	8.6	9.2
Ethanol fermentation	0.0	10.0	10.0	8.5	7.5	0.0
Biodiesel production	3.5	0.0	1.4	2.3	3.4	5.3
Burner, turbo-generation	0.0	27.7	29.7	31.5	36.0	41.8
Storage	5.3	0.8	1.3	1.7	2.0	1.7
Utilities (e.g. cooling tower)	0.3	1.5	1.7	1.7	1.9	2.7
Total equipment cost	26.6	50.3	54.9	56.6	61.9	63.2
Fixed capital investment (3×total equipment cost)	79.9	151.0	164.7	169.8	185.7	189.5
Working capitall (5% of fixed capital investment)	4.0	7.5	8.2	8.5	9.3	9.5
Total capital investment	83.9	158.5	172.9	178.3	195.0	199.0

[a]For the soybean biodiesel process, the oil/sugar extraction and purification sections includes coproduct processing (soybean hulls and soybean meal).

MT of sugarcane (Fig. 3). This number agrees with previous studies, where the ethanol yield per MT of sugarcane was between 82 and 93 liters.[27, 29, 42, 45] These results confirm the validity of the data obtained from our model and the assumptions considered. For the lipid-cane with 2% lipids, 6.0 liters of biodiesel and 79.9 liters of ethanol were produced per MT of lipid-cane. As the lipid content increases, the ethanol production decreases, but the biodiesel production increases. This result makes sense because more sugar was diverted to produce oil. For the lipid-cane with 20% lipids, 60.1 liters of biodiesel can be produced from each MT of lipid-cane, but no ethanol was produced due to the little sugar remaining in the lipid-cane.

Electricity from bagasse plays an important role in modern sugarcane processing plants.[46–48] In the sugarcane plant, bagasse is burned to produce steam and electricity for the plant,[46] with the surplus electricity sold to the grid to generate co-product credits. The steam and electricity requirements for the processes of soybean biodiesel, sugarcane, and lipid-cane with 10 and 20% lipid contents are shown in Table 7. It is worth notice that the steam requirement for the lipid-cane with 20% lipid was significantly lower compared to that for the sugarcane and lipid-cane with 10% lipid. This is because all sucrose has been converted to TAGs in this scenario and so there is no fermentation or ethanol evaporation when lipid-cane with 20% lipid, so the steam usage was low. The electricity used by the sugarcane and lipid-cane processing plants

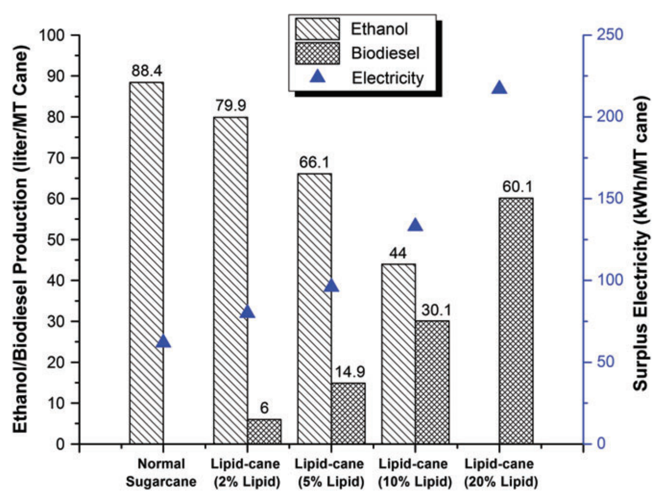

Figure 3. Main product and coproduct (surplus electricity) yields from each MT of normal sugarcane and lipid-cane.

were between 50 000 and 53 000 MWh per year, which corresponded to approximately 31 to 33 MWh per MT of sugarcane processed. It is should be noted that due to the combustion of bagasse, no external energies (i.e., fossil fuel) is needed at modern the sugarcane processes. This makes sugarcane process self-sustainable in energy.[29]

The surplus electricity production is approximately 61 kWh per MT of sugarcane (Fig. 3). This number is slightly lower than the previously reported value of 68 kWh per MT of sugarcane.[29] According to the UNICA report, up to 96 kWh total electricity (electricity used in the process

Table 7. Utility utilization for the processes of soybean and sugarcane (0, 10, and 20% lipids).

Utilities	Soybean	Sugarcane (0% lipid)	Lipid-cane (10% lipid)	Lipid-cane (20% lipid)
Electricity (Mw-h)	24,232	50,187	52,644	52,687
Steam (MT)	0[a]	686,056	656,000	102,609
Natural gas (MT)	9,001	0[b]	0[b]	0[b]

[a]Steam is generated by burning natural gas in the soybean-biodiesel plant.
[b]Bagasse is burned to generate steam, so no natural gas is used in the sugarcane processing plant.

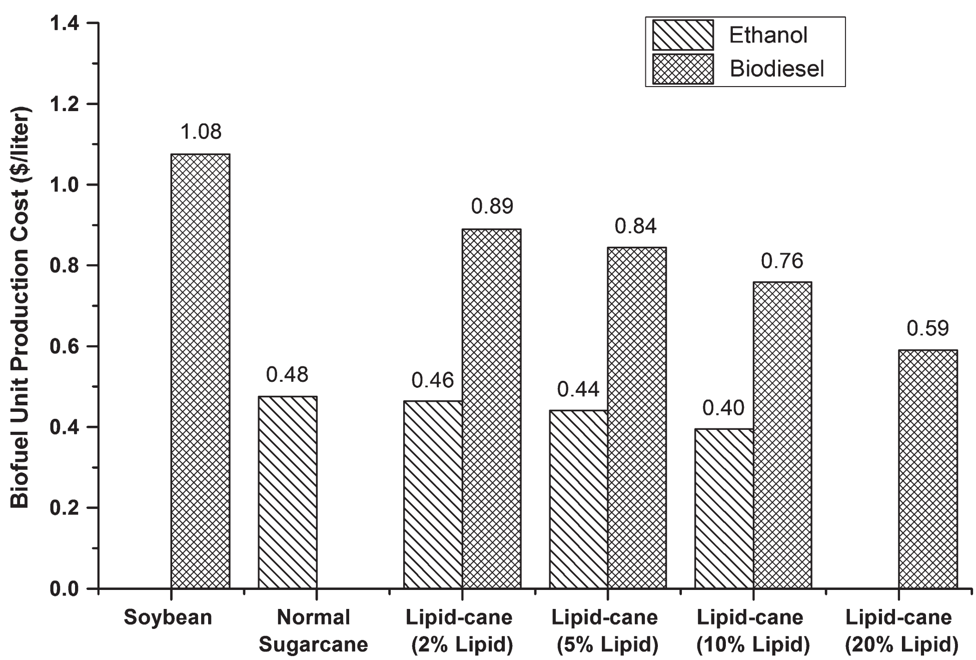

Figure 4. Biofuel unit production costs from soybean, normal sugarcane, and lipid-cane.

plus surplus electricity) can be generated using the latest extraction-condensation technology.[28] With the increase in lipid content, the surplus electricity production increases substantially due to the higher fraction of fiber in the lipid-cane. Furthermore, only 90% of the lipids in the lipid-cane were extracted in the extraction process, where as the rest 10% of the lipids remained in bagasse and was burned in the cogeneration system, which further increased the electricity production.

The resulting unit production costs for biodiesel and ethanol are shown in Fig. 4. The biodiesel production cost from soybeans is estimated to be $1.08/liter. In the USA, the bulk petroleum diesel fuel prices during 2013 were generally in the range of $0.82–0.98/liter,[9] which was lower than the production cost of the soy biodiesel estimated here. This finding indicates the economic difficulty of the soy biodiesel process without policy support. The biodiesel production cost from 2% lipid-cane was $0.89/liter, which was lower than that from soybean. The remaining sugar in the 2% lipid-cane was fermented to produce ethanol at a production cost of $0.46/liter, which could further improve the economics of the lipid-cane process. With the increase in lipid content, both the biodiesel and ethanol production costs from the lipid-cane decreased accordingly. As the lipid content increased to 5%, the biodiesel and ethanol production costs decreased to $0.84 and $0.44/liter, respectively. The lower production cost of lipid-cane is primarily attributed to the lower feedstock cost of lipid-cane compared with that of soybean. As the lipid content increased to 20%, the biodiesel production cost further decreased to $0.59/liter, which made it competitive with petroleum diesel.

The details of the unit production costs of processes with different feedstocks are shown in Table 8. For conciseness, only the production costs from soybean, normal sugarcane, and lipid-cane with lipid contents of 10 and 20% are

Table 8. Annual production and unit cost for the processes of soybeans and sugarcane (0, 10, and 20% lipids).

Item	Soybean	Sugarcane (0% lipid)	Lipid-cane (10% lipid)	Lipid-cane (20% lipid)
Production (million liter/yr)				
Biodiesel production	96.0	-	48.0	96.0
Ethanol production	-	141.0	70.0	-
Raw Material cost (million $/yr)				
Feedstock	266.1	55.3	55.3	55.3
Other chemicals	6.5	3.7	6.2	7.8
Utilities	4.0	-	0.2	0.5
Labor	3.5	3.5	3.5	3.5
Supplies	1.3	2.0	2.4	2.4
General works	0.9	1.7	2.0	2.1
Capital charges (Depreciation)	4.0	7.5	9.3	9.5
Co-product credit	-182.7	-6.5	-14.6	-24.3
Total operating cost	103.5	67.2	64.3	56.8
Operating cost allocation[a] (million $/yr)				
Biodiesel	103.5	-	36.5	56.8
Ethanol	-	67.2	27.8	-
Unit production cost ($/liter)				
Biodiesel	1.08	-	0.76	0.59
Ethanol	-	0.48	0.40	-

[a]The operation cost is proportionally allocated to each of the main products with respect to their marketing values, if there are two main products in the process. The marketing value of each product is determined by the annual production multiplied by its selling price. In this study, the selling prices of biodiesel and ethanol are set to be $1.22/liter and $0.62 /liter, respectively, based on the average price in the USA in 2013.

presented. For all processes, raw material costs constituted the largest portion of the total operating cost, and of the raw material costs, the feedstock costs (i.e., soybeans, sugarcane, and lipid-cane) accounted for the largest portion. Therefore, feedstock costs are the main contributor to the biodiesel and ethanol production costs. Similar estimates that the feedstock cost was the greatest contribution to the biodiesel production cost were reported in other studies.[2,11,49] Due to the lower feedstock cost, the biodiesel production cost from the lipid-cane process is lower than that from the soybean process.

Profitability analysis

Because the lipid-cane process has a much higher total capital investment than the soy-biodiesel process does, the lower biofuel unit production cost of the lipid-cane process may not necessary indicate a better economic performance. Therefore, the IRR was calculated to evaluate the economic performance of each scenario (Fig. 5). Despite the lower unit biodiesel production cost compared with the conventional soy-biodiesel process, the process of lipid-cane with 2% lipid content had a lower IRR due to its higher total capital investment. However, it has a slightly higher IRR than the normal sugarcane process. The IRR value of the lipid-cane process increases as the lipid content increases. When the lipid content increases to 5%, the IRR value of the lipid-cane process becomes comparable to that of the soy-biodiesel process. For the 20% lipid cane, there was no sugar left in the stem; thus, no sugar separation, fermentation, or distillation was needed in the process, which significantly reduced the related capital and energy costs. Therefore, when the lipid content in the lipid-cane increased from 10 to 20%, the IRR value of the process increased remarkably from 17.5 to 24.0%. The IRR of the 20% lipid content lipid-cane process was much higher than that of the soybean process.

Sensitivity analysis

Senstivity analyses were performed to test variables that were uncertain and those were found to significantly affect

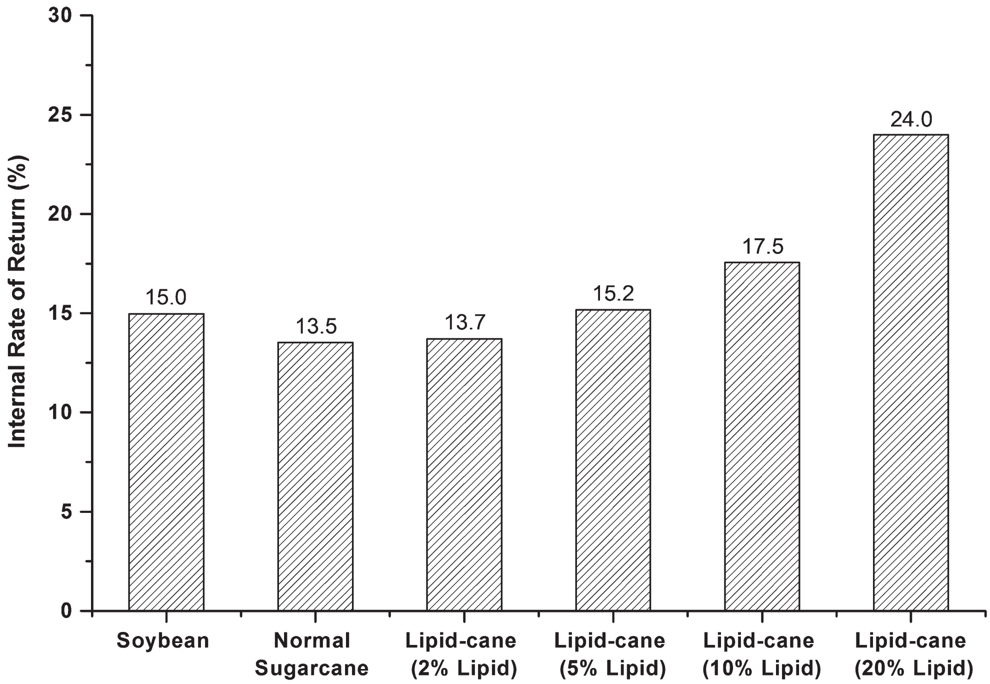

Figure 5. Internal rate of return of the soybean, normal sugarcane and lipid-cane processes.

the biodiesel production cost (Fig. 6). Two cases were analyzed. The first case was the process of lipid-cane with 10% lipid concentrations, and the second case was the soybean-biodiesel process. In both cases, low and high points were chosen, which were then combined to give an estimate of the accumulated effect of the various parameters changes on the biodiesel production costs (Fig. 7).

First, we varied the cost of lipid-cane price, as there is significant uncertainty regarding lipid-cane costs and these have a very large influence on the biodiesel production cost. The cost of lipid-cane price was based on the average sugarcane price in 2013. It is possible that the genetically modified lipid-cane would have a higher price compared to normal suagrcane, due to its higher lipid content and research investment. The uncertainties in biomass yield of the lipid-cane would also influence its price. The lower biomass yield would probably cause the increase of lipid-cane price to balance farmer's income. However, it would also be very possible that biomass might increase due to the synergy effect of lipid accumulation and carbon assimilation[20, 50] and current research on photosynthesis improvements of crops.[51] Therefore, a larage variation of lipid-cane price ($25 to $45/MT) was selected for sensivitiy analysis. As the cane price variates between $25/MT and $45/MT, the biodiesel production costs change broadly between $0.57/liter and $0.95/liter.

Besides the lipid-cane price, the lipid extraction efficiency is also of importance. Since the lipid-cane is a new engineered crop to produce lipid, there is a significant unceratinty redarding extraction efficiency. Therefore, a range of extraction efficiency from a low point (70%) to a high point (95%) was selected for sensitivity analysis. Interstingly, its influence was not as large as other variables, such as lipid-cane prices, annual operating days and annual cursh capacity. This is mainly because the unextracted lipids were burned to produce electricity, which increased the coproduct credits. Furthermore, glycerol selling prices had little influence on the biodiesel production costs.

In the case of the soybean biodiesel process, the soybean prices and soybean meals were the main targets for sensitivity analysis, since these two parameters had the largest influence on the biodiesel production cost. Both parameters are uncertain due to the large fluctuations of marketing prices of soybean and soybean meals. In 2013, the monthly average prices for soybean fluctuated between $470 and $560 per MT, and the monthly average prices for soybean meal fluctuated between $450 and $520 per MT.[52] By excluding the extreme prices, the soybean price between $490 and $550 per MT and the soybean meal price between $450 and $500 per MT were conducted for sensitivity analysis. Compared to the above two variables, other variables (i.e., soybean hull prices, glycerol price,

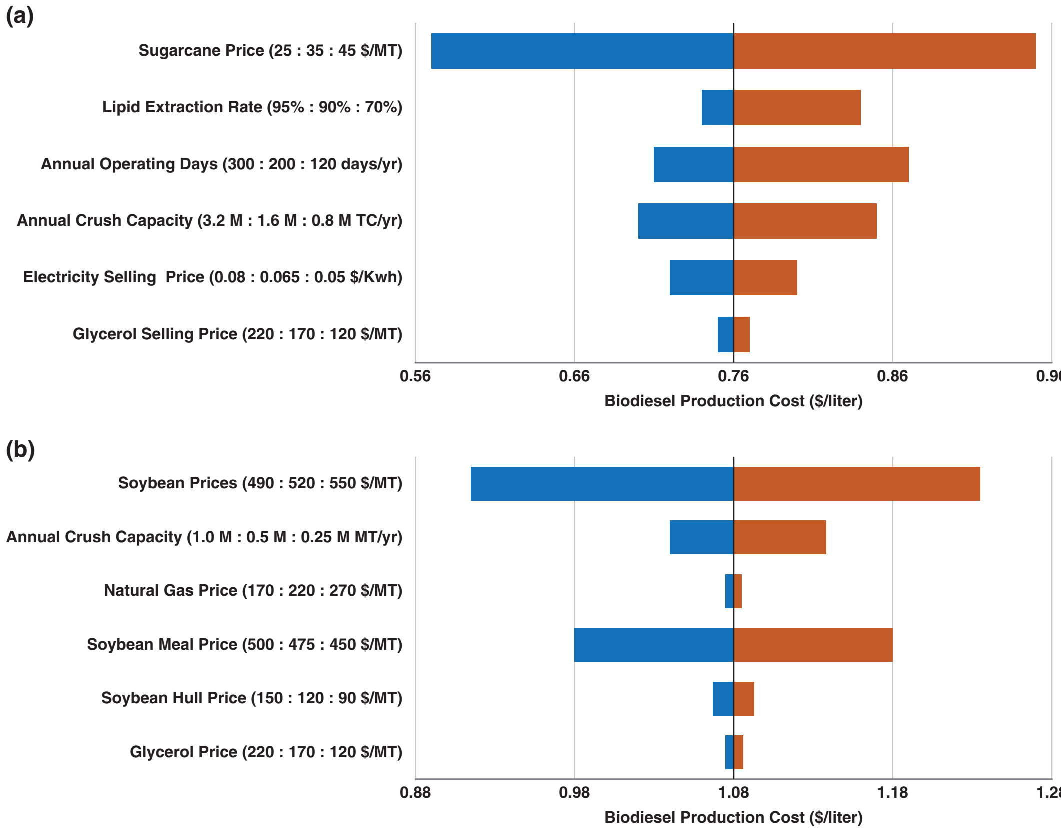

Figure 6. Sensitivity of biodiesel production cost to different parameters. (a) Lipid-cane process; (b) Soybean process. The numbers in brackets in Y-axis are the potential low, base and high values of each parameter.

and natural gas prices) did not have large influence on the biodiesel production cost.

Figure 7 shows the combined effect of parameter variations on the biodiesel production cost. The range of biodiesel production cost for both cases were wide because of the uncertainty in these variables. The wide range of the estimated cost could become narrow as technology develops, because some varibales would become consistent, such as lipid extraction efficiency. However, some parameters, such as soybean price, remain uncertain, since they are more market-driven.

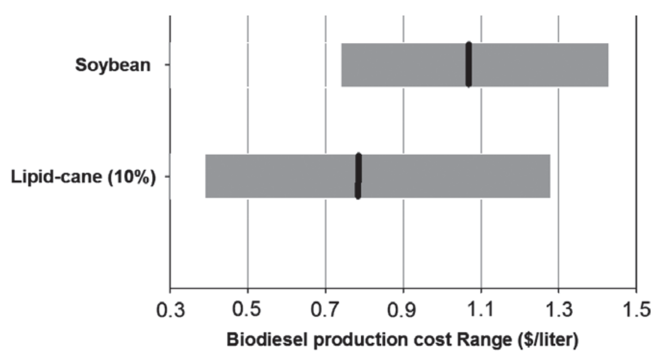

Figure 7. Accumulated uncertainties of the sensitivity parameters on the biodiesel production cost. The base values are included for reference as a vertical bar.

Biofuel yield per unit land area

Though it is important to understand the biofuel production costs and the IRR for the soybean and lipid-cane processes, it is equally important to evaluate the amount of biofuel production from each hectare of land use because the limited land resource is one of the main barriers for the wide replacement of petroleum fuel with biofuel. Sugarcane has advantages of higher productivity versus oilseed crops (e.g., soybean and canola). In the USA, the average yield of soybean is approximately 2.8 MT/ha.[24] The normal sugarcane yield in the most productive zone of the USA (Hawaii) can be as high as 180—220 MT/ha, though this value decreases to 75–110 MT/ha in the south-

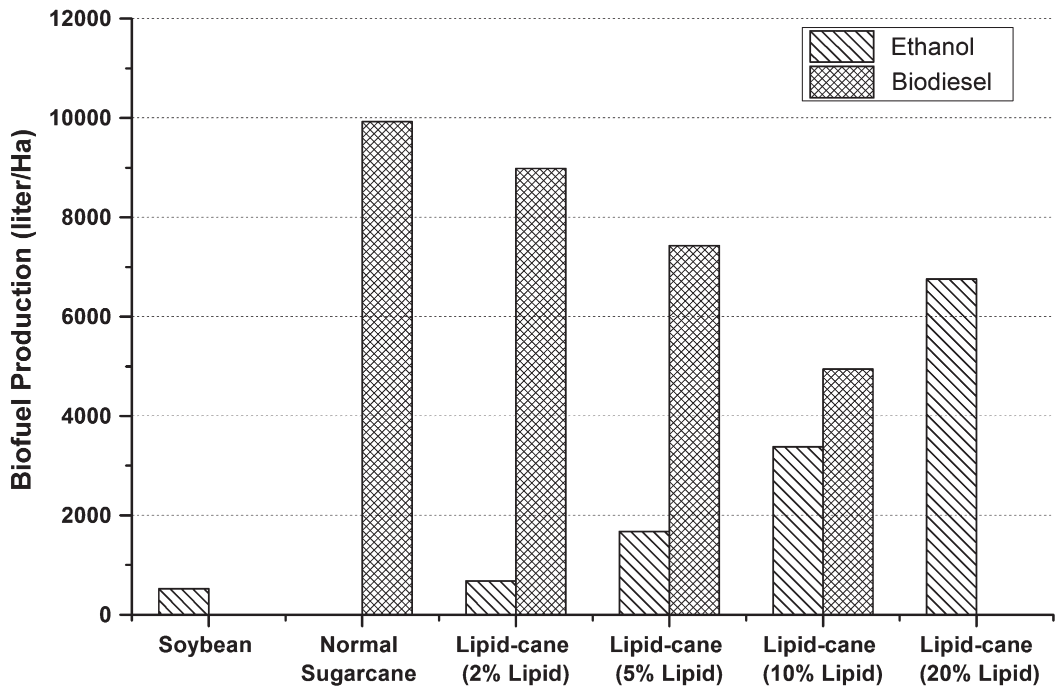

Figure 8. Biofuel production per hectare of land use by soybeans and lipid-cane. The soybean yield was assumed to be 2.8 MT/ha, and the lipid-cane biomass yield was assumed to be 110 MT/ha. The soybean moisture content was 13%, while the cane moisture content was 70%.

ern states of the USA (Florida, Louisiana, and Texas). In this study, the lipid-cane yield was assumed to be the same as that of conventional sugarcane at 110 MT/ha, with 70% moisture content. Using the biofuel yields from each MT of sugarcane and lipid-cane, the biofuel production per hectare of land use can be determined. Figure 8 shows that the biodiesel yield from soybeans is only approximately 500 liters per hectare of land use. For the lipid-cane, even with 2% lipid content, the biodiesel yield was already higher than that from soybean. Meanwhile, it can produce nearly 10 000 liters of ethanol by fermenting the remaining sugars. Upon increasing the lipid content from 2 to 20%, the biodiesel yield increases, where as the ethanol yield decreases because the sugar in the lipid-cane was replaced with the lipids. For the lipid-cane with 20% lipid content, planting lipid-cane on one hectare of land can produce more than 6700 liters of biodiesel, which is more than 10 times that of soybean. With such high biodiesel production from each hectare of land, it only needs about 0.76 Mha of land to meet the current US biodiesel requirement (5.1 billion liters). Given a total current managed farm land area of 370 Mha with an additional 11 Mha in conservation reserve, 0.76 Mha is a realistic target.[53]

Conclusions

A techno-economic model of lipid-cane processes to produce ethanol and biodiesel was developed and compared with a soybean-based process model to assess lipid-cane's economic competitiveness. By increasing the lipid content in lipid-cane from 2% to 20%, the biodiesel production costs decreased from \$0.86/L to \$0.59/L, which is lower than the production cost from soybeans, \$1.08/L. The IRR values of the lipid-cane processes are dependent on the lipid content in lipid-cane: as lipid content increased from 2 to 20%, the IRR values increased from 13.5 to 24.0%. Therefore, it is important to increase the lipid content to make the lipid-cane more competitive. Due to its high productivity, lipid-cane can produce more than 10 times the amount of biodiesel per hectare than soybeans. Overall, the techno-economic model shows that lipid-cane could be a promising alternative feedstock for biodiesel and ethanol production.

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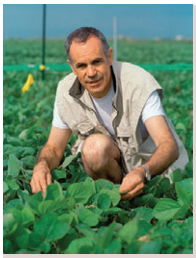

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