processes

Article

An Environmental and Economic Analysis of Flocculation Technology Applied to a Corn-Based Ethanol Plant

Maria da Conceição T. B. e Oliveira [1], Kurt A. Rosentrater [2,*]

[1] Department of Agricultural and Environmental Engineering, Federal University of Mato Grosso, Rondonópolis 78700, Brazil; marya@iastate.edu
[2] Department of Agricultural and Biosystems Engineering, Iowa State University, Ames 50011, USA; karosent@iastate.edu
* Correspondence: karosent@iastate.edu (K.A.R.); Tel.: +1-515-294-4019

Received: 27 November 2019; Accepted: 24 February 2020; Published: 27 February 2020

Abstract: The stimulation of renewable fuel production is related to the environmental issues resulting from the extraction and utilization of fossil fuels. Although corn-based ethanol is one of the leading renewable fuels and promises to mitigate these environmental impacts, it generates large volumes of wastewater with high concentrations of organic material (COD_{cr} > 30,000 mg/L) and low pH (3.5–4.5), which leads to serious environmental concerns. A common method of treatment of distillery wastewater is the Dry Distilled Grain Soluble (DDGS) process, which separates liquid and solid fractions; however, a disadvantage of this process is its high energy consumption. Other commonly implemented methods are often costly and not environmentally safe. To minimize these problems, a flocculation process can be applied as a potential lower energy consumption process utilizing bioflocculants, which have been proven harmless to the environment. Therefore, the main goal of this study was to analyze the economic and environmental impacts of using bioflocculants instead of evaporation process in a corn-based ethanol plant. The procedures were evaluated by analyzing the Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA). From the results, it can be seen that the flocculation system can be an alternative process for effectively minimizing energy consumption during the production of DDGS, Distilled Wet Grains with Solubles (DWGS), and corn oil. The flocculation process achieved a significantly (28%) lower utility cost when compared to the conventional system. However, the overall fixed costs and annual operating costs for the flocculation system were higher than those of the conventional system. Additionally, both processes resulted in negative profit and a sensitivity analysis showed that the feedstocks cost substantially impacted the DDGS, DWGS, and corn oil production costs. Related to environmental aspects, the LCA results showed that the flocculation process achieved the lowest Global Warming Potential (GWP) of the several electricity supply technologies analyzed and presented a significant reduction in CO_2 equivalent emissions when compared to a conventional system. The flocculation process resulted in approximately 57% lower greenhouse gas emissions.

Keywords: ethanol; wastewater; bioflocculants

1. Introduction

Consumption of liquid fuels has increased significantly over the last few decades, with annual global oil consumption expected to reach 100 million barrels per day by 2019 [1]. Researchers have therefore expended their efforts toward developing sustainable technology for producing liquid fuels with features such as energy source diversity, mitigation of greenhouse gas (GHG) emissions, and minimization of other pollutants that can negatively impact both the environment and inhabitants' health [2]. Among the "first-generation biofuels," ethanol, biodiesel, and pure plant oil (PPO) are the most common biofuels [3].

Ethanol is produced from the fermentation and distillation of sugar- or starch-based raw materials, and can be used either as a pure fuel or blended with gasoline for spark-ignition vehicles [4]. Many feedstocks can be used as raw material to produce ethanol. However, for producing ethanol of the first generation, corn, sugarcane, and wheat are the most common feedstocks used. The two major global ethanol producers, the United States and Brazil, use corn and sugarcane as feedstocks, respectively [5].

Because of doubts related to the extent to which ethanol as a replacement for fossil fuels can minimize greenhouse gas (GHG) emissions, several studies focusing on the biofuel life cycle have been conducted to address this question [2,6–11].

The environmental impact of products and services in ethanol production can be evaluated using Life Cycle Assessment (LCA), considering the whole product life cycle in addressing the environmental issues of the product system. To evaluate the whole chain of one product or service (cradle to grave), goal and scope definitions, inventory analysis, impact assessment, and interpretation have to be considered as the four main LCA stages [12]. A Techno-Economic Analysis (TEA) can be used for estimating the costs of a new technology.

With respect to ethanol production, the amount of wastewater produced and the techniques used to manage its treatment are a consistent environmental concern. To achieve lower costs and minimization of environmental impacts, different treatments have been tested, focusing on more effective use of innovative treatment technologies [13].

Since the evaporation process is associated with high energy consumption, flocculation might be an effective alternative for minimizing energy consumption and the consequent environmental impact. Therefore, the main objective of this study was a life cycle assessment (LCA) and techno-economic analysis (TEA) of the flocculation process as a replacement for an evaporation process in ethanol production.

2. Ethanol and coproducts production

Distillers' Wet Grains (DWG), Condensed Distillers' Solubles (CDS), also known as "syrup," and the combined product Distillers' Dried Grains with Solubles (DDGS) are the main coproducts associated with corn ethanol production [14]. Nonfermentable coproducts, produced from a dry grind process, are commonly in the form of distillers' wet grains (DWG) or distillers' dried grains with solubles (DDGS), while coproducts in a wet milling process are in the form of corn gluten meal or corn gluten feed [15].

For producing ethanol from corn, the corn must first be processed to break down its starch into usable sugars. Dry grind processing, most commonly used to convert corn into ethanol, consists of grinding the corn, using enzymes to convert the resulting starch into sugar, and using yeast to ferment the sugar into ethanol [15,16]. Since in this process it is necessary to minimize the capital investment, it is desirable to exploit the production of coproducts with low value [16].

Coproducts are considered to be additional sources of revenue to ethanol plants. DDGS usually contains about 86%–93% (db) dry matter, 26%–34% (db) crude protein, and 3%–13% (db) fat, although DDGS composition can vary among plants [17]. After examining the compositional differences in DDGS from U.S. plants from 12 states, [18] stated that the ranges were: for dry matter, 87.9% to 90.6%: for ash content, 4.2% to 6.6%; for protein content, 29.4% to 32.6%; for fat content, 9.6% to 12.8%; and for crude fiber content, 6.7% to 9.3%.

3. The Flocculation process as a treatment for wastewater

A considerable amount of wastewater is generated in ethanol production from the corn ethanol plant. Whn manufacturing each liter of ethanol, around 13 liters of wastewater are produced, which presents a biological oxygen demand (BOD) of 18,000–37,000 mg/L, depending on the specific type of plant production [19].

Wastewater is typically compounded by solids not recovered either as primary products or coproducts. A lack of wastewater treatment can be reflected in lost products or coproducts because the wastewater from most food processes contain protein, vitamins, and minerals, possible sources of animal feed [16].

Both physicochemical and biological methods have been developed for treating wastewater, which presents a high chemical oxygen demand (COD), biochemical oxygen demand (BOD), organic contaminants content, and dark color. These methods offer some disadvantages and limitations, such as a minor effect on color removal and the high energy involved. However, some alternative methods such as flocculation, coagulation, an advanced oxidation process, bacteria and fungi, and membrane technology have been investigated [20].

Knowledge of wastewater properties is essential in designing a treatment process. For domestic and industrial wastewater, a biological wastewater treatment, using microorganisms to degrade pollutants under anaerobic or aerobic conditions is frequently considered a feasible and cost-effective treatment method. In a biological treatment process, organic and inorganic compounds are transformed into H_2O, CO_2, N_2, etc., to accomplish the complete mineralization of wastewater pollutants [21].

Mechanical removal of suspended particles, anaerobic treatment, aerobic treatment, and recycling are other techniques that can be used to minimize the number of organic pollutants contained in wastewater [4]. For a cellulosic biorefinery waste stream, [22] affirmed that lignin is the main constituent remaining in the waste stream, in addition to 15 L of process water per liter of ethanol produced. A study by [23] found remaining constituents of 79 wt % lignin, 8.3 wt % cellulose, and 3.6 wt % hemicellulose. Wastewater also contains nonutilized fermentable sugars and process chemicals, in addition to solid fractions, that form stillage [22].

The flocculation process could be a potential alternative to wastewater treatment from the perspective of using the remnants efficiently. The main objective of the flocculation process is to form aggregates that can be removed by a sedimentation or flotation process. The aggregates are originated from the combination of individual destabilized colloidal particles, combined with others and with the precipitate formed by the coagulant. Some crucial considerations in this process are the flocculation time that governs the floc formation, and the flow velocity, which must be higher than 0.15 and lower than 0.5 m/min with a retention time of at least 30 min [24].

4. Flocculants in the flocculation process

In most cases, chemical flocculants can negatively impact the environment and health. Bio-based flocculants, a type of biodegradable macromolecular flocculants, can advantageously replace chemical flocculants by being biodegradable and less harmful to the environment [25,26].

Piazza et al. [27], based on their research, pointed out that flocculants can be used in a large variety of processes to accomplish various objectives such as wastewater clarification, paper manufacturing, dewatering and thickening in mineral operations, and filtration and centrifugation aids.

Bio-based flocculants can either be produced by microorganisms such as bacteria and fungi, or extracted from natural resources, such as trees [28]. Zhao et al. [25] studied the production and optimization of bio-based flocculants by using wastewater supernatant from corn straw and molasses wastewater from anaerobic digestion (AD) to remove heavy metals. They produced relevant results and concluded that such wastewater could be used to produce bio-based flocculants for effectively removing heavy metals from electroplating wastewater.

Studies have shown that animals' blood, such as bovine and porcine blood, and purified bovine hemoglobin can serve as effective flocculants of clay at pH values lower than the protein isoelectric point, which indicates that protein must have a net positive charge [29,30]. Chicken blood was tested as a substitute for synthetic flocculants by Piazza et al. [27], with results showing that chicken blood fractions performed similarly to or better than the anionic polyacrylamide (PAM), a polymeric flocculant widely used because of its low toxicity to aquatic life. These authors analyzed various fractions of chicken blood: the supernatant from centrifugation of whole blood at 5200 × g (2 × 10 min), the supernatant from centrifugation of heated whole blood was stirred on a hot plate at about 1 °C per minute, until the temperature reached 75 °C, when coagulation occurred, subsequently centrifuged at 5200 x g (2 x 30 min), followed by a dehydration process. The authors estimated the production costs of flocculants from chicken blood to be $0.77 per pound ($1.77/kg).

5. Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA)

For ethanol processes, life cycle assessment (LCA) has been used to assess the environmental impact of its products and services, focusing on greenhouse gas (GHG) emissions and energy balance, with less attention paid to the wider range of environmental impacts [11,31,32]. Depending on the purpose of such analysis and interpretation, the life cycle assessment (LCA) of greenhouse gas (GHG) emissions calculations should conform to International Standards Organization (ISO) standards guidelines ([32]. The ISO has defined both principles and a framework (ISO 14040, 2006) , set requirements, and provided guidelines for LCA (ISO 14044, 2006).

Quantification and evaluation of the environmental performance of a product, process, or activity from “cradle to grave” is a principal objective of life cycle assessment (LCA); another aim is to help decision-makers in choosing among alternative products or processes to achieve minimum levels of greenhouse gas (GHG) emissions [33].

Techno-economic analysis is a tool used to reveal the total cost of a process, and can be used for analyzing optimization efficiency of a new process or technology applied in a system. Some common criteria used in techno-economic analysis are cash flow, discounted cash flow, net present value (NPV), internal rate of return (IRR), payback period (PP), and sensitivity analysis [34]. Thus, when related to potential environmental impacts, techno-economic analysis and assessment can be used to identify the most promising technologies that can be applied to the system under study [35].

6. Methodology

A corn-based ethanol plant was used in this study, simulating the replacement of evaporation process by the flocculation process as a new technology for minimizing energy consumption and consequently minimizing the end-user cost of the products. The USDA model for a 40 million gal/y dry grind corn ethanol plant, created by Kwiatkowski et al. [36] using SuperPro Designer (Intelligen, Inc., Scotch Plains, NJ, USA), was utilized as a basis for conducting the simulation.

Two scenarios were used to conduct a life cycle assessment (LCA) and techno-economic analysis (TEA); simplified flow diagrams of both are shown in Figures 1 and 2. The first scenario was based on a conventional corn-based ethanol plant that utilizes an evaporation process (Figure 1), and the second scenario considered the substitution of the evaporation process by a flocculation process, aiming to mitigate the energy consumption and maximize the environmental benefits when compared to the first scenario (Figure 2).

Life cycle assessment was conducted considering the “gate-to-gate” environmental impacts of producing corn-based ethanol coproducts, and the studied system includes whole stillage from distillation to coproducts from ethanol production using the dry milling technology associated with flocculation technology.

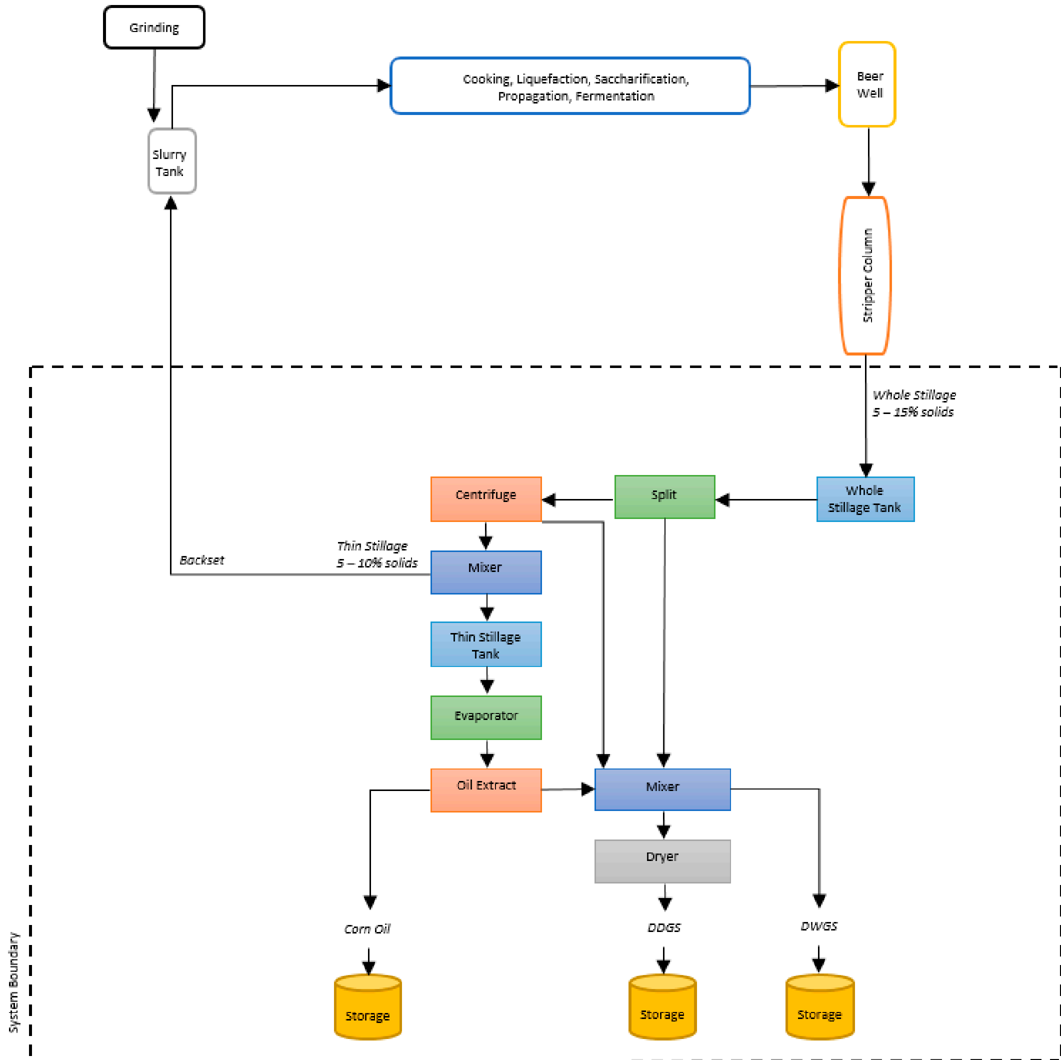

Figure 1. Simplified flow diagram of a conventional corn-based ethanol plant flow chart (Scenario I). The system boundary includes tanks, splitter, centrifuge, mixers, dryer, evaporator, and storage systems.

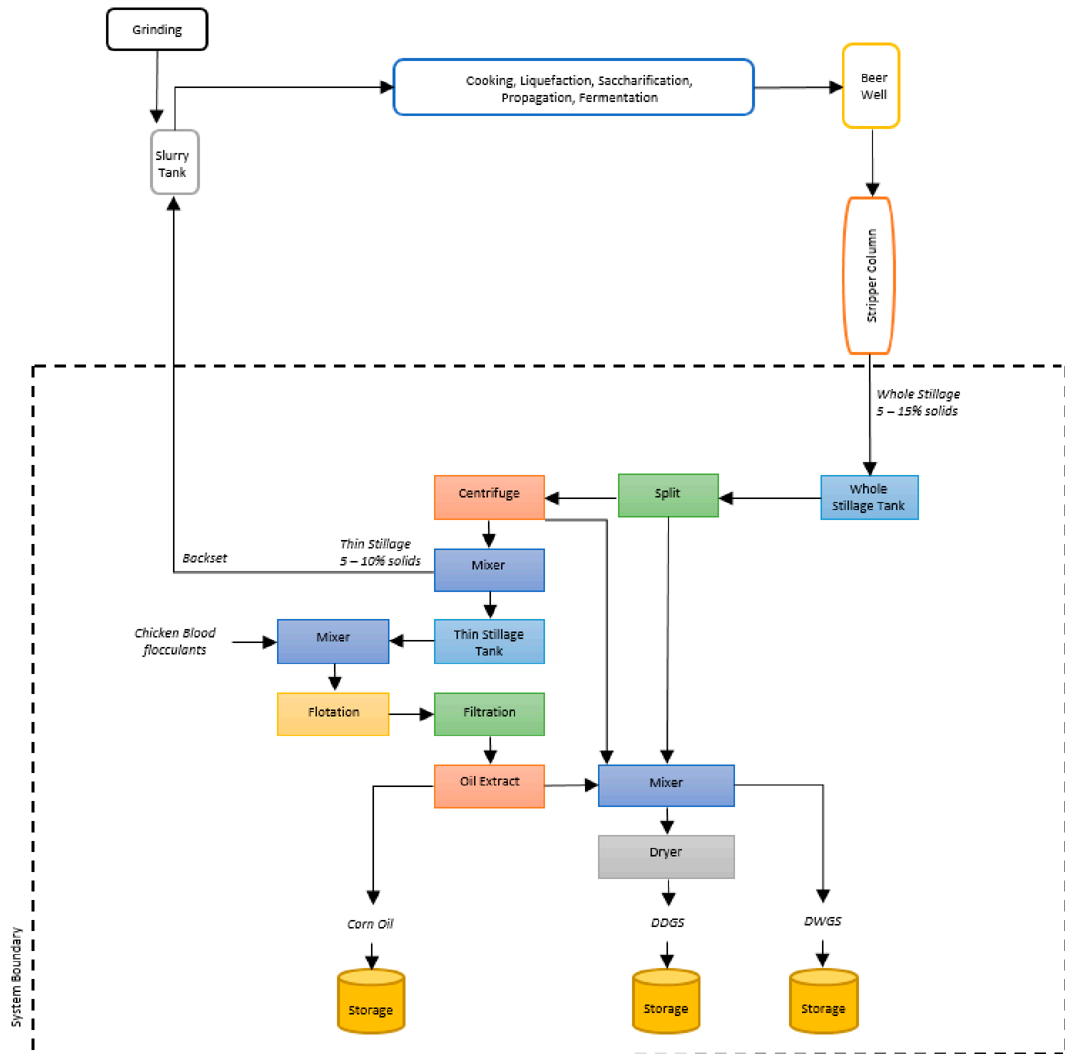

Figure 2. Simplified flow diagram of a corn-based ethanol plant with flocculation process (Scenario II). The system boundary includes tanks, splitter, centrifuge, mixers, dryer, flotation, filter, and storage systems.

7. Computer modeling

SuperPro Designer v10 (Intelligen, Inc.) was used to perform the economic model for quantifying the processing characteristics, energy requirements, and equipment parameters, considering each operating scenario. This industrial designing software determines the mass and economic balance of each unit operation and of the whole system by providing the flow rate, chemical composition, physical and economic properties of each stream. Techno-economic analysis (TEA) for each scenario was conducted by using spreadsheet (MS-Excel) software based on SuperPro economic outputs.

In the first scenario, the system boundary includes tanks, splitter, centrifuge, mixers, dryer, evaporator, and storage systems. In the second scenario, the system boundary includes tanks, splitter, centrifuge, mixers, dryer, flotation, filter, and storage systems, considering a corn-based ethanol plant. The functional unit for greenhouse gas emissions in both scenarios was related to ton of whole stillage processed (kgCO_{2eq}/t of whole stillage processed) due to whole stillage being considered the raw material used for both scenarios.

8. Assumptions and Data Collection

Economic costs were calculated based on capital, variable, and fixed costs. Capital costs include equipment costs, installation costs, electrical costs, piping costs, and construction costs, while variable costs are associated with utility costs, labor costs, raw materials costs, maintenance and repair costs, and other supply costs. Fixed costs include expenses related to insurance, depreciation, interest, overhead, and taxes.

For both scenarios, the model was set up to operate on the basis of 330 d/y with a work schedule of 24 h/d, considering time for maintenance and repairs and using a common ethanol plant operational system [15]. The nominal capacity of the plant in the model was taken to be 2000 dry tons (t) per day of raw material, similar to that in the study conducted by Dutta et al. [37].

For conducting the simulation, the thin stillage composition was based on the values published by [38] and by [17]. It was assumed that the whole stillage contained 15% solids and the thin stillage contained 10% solids. Chicken blood (CKB) was used as the flocculant in the flocculation process used in the second scenario. The CKB blood composition values were based on the values stated by Del Rio De Reys et al. [39]. Thin stillage and CKB blood compositions are listed in Table 1.

Table 1. Thin stillage and chicken blood compositions utilized to conduct the simulations, adapted from values published by [17,38,39].

Nutrient	Thin stillage (% DM basis)	Chicken blood (% DM basis)
Starch	22.0	-
Crude protein	16.8	80.21
NDF	11.7	-
Fat	8.1	0.2
Ash	5.9	4.6
Ethanol	12.2	-
Dry matter	5.0	-
Carbohydrate	-	14.99

The required amount of CKB flocculant was calculated based on the thin stillage volumetric flow, considering that 1 g of CKB flocculant was needed for each liter of thin stillage to be processed.

For the TEA model, the assumptions were: 20 years of plant lifetime, 30 months of construction time, six months of startup time, 35% income tax, a 10-year depreciation period with 5% salvage value of direct costs, 10% per year interest rate for debt financing, and 100% equity. The detailed material and energy flow presented by the model and the unit costs used in the design report were used to determine operating costs.

To estimate total capital costs for both scenarios (Table 2), the methodology utilized by Brown and Brown [40] was followed.

Table 2. Methodology and assumptions used for total capital cost investment estimations.

Parameter	Assumptions
Total Purchased Equipment (TPEC)	100%
Purchased equipment installation	39% of TPEC
Instrumentation and controls	26% of TPEC
Piping	10% of TPEC
Electrical systems	31% of TPEC
Buildings (including services)	29% of TPEC
Yard improvements	12% of TPEC
Service facilities	55% of TPEC
Total Installed Equipment Cost (TIEC)	TPEC × sum of installation factors (302%)
Total Indirect Cost (TIC)	TPEC × sum of IC factors (89%)
Engineering	32%
Construction	34%
Legal and contractors' fees	23%
Total Installed Equipment and Indirect Costs	TIEC + TIC
Contingency	(TIEC + TIC) × 20%
Fix Capital Investment (FCI)	(TIEC + TIC + contingency) × Local Factor
Working Capital (WC)	15% of FCI
Land Use	6% of TPEC
Total Project Investment (TPI)	FCI + WC + Land

Source: [40]

Fixed capital investment (FCI) was determined by the full cost of the facility that could be depreciated, and was calculated considering the purchased equipment costs, installation costs, indirect costs, and contingency, multiplied by a location factor (LF). According to [40], the location factor reflects differences in dominating costs in other regions and countries by assuming that the simulated facility is located in a region or country without an established refining industry. For this study, the location factor was taken as 1.0 for both scenarios.

Variable costs were estimated based on [40] methodology. The raw materials cost ($/y) was calculated according to Equation (1). Whole stillage and CKB blood were the raw materials considered in the models; however, the cost for CKB blood was included only in Scenario II. While [27] estimated the cost of flocculant production from CKB blood to be $0.77 per pound ($1.70 per kilogram), since information about the whole stillage cost could not be found in the literature, in conducting the TEA, the whole stillage price was calculated based on the protein–fiber (%PF) ratio of DDGS and the whole stillage, acknowledging that the DDGS price is based mainly on the protein and fiber content. Thus, considering that DDGS had a 35% PF with an average price of $150.00/t in January [41] and whole stillage had a 1.5% PF, the whole stillage price estimation was $6.43/t.

The capacity factor (f_0) shown in the raw material cost equation was the fraction of time a facility operates on an annual basis, which was calculated based on 330 working d/y.

$$Raw\ material\ cost\ \left(\frac{\$}{y}\right) = C_R\ x\ \dot{m}\ x\ 31.5\ x\ 10^6\ x\ f_0 \quad (1)$$

where: C_R – unit cost of raw material ($/kg); $\dot{m}$– feed rate (kg/s) of raw material into plant; 31.5 × 10^6 s/year corresponds to the total of seconds per year; f_0 – capacity factor of a facility.

The operating labor cost was considered to be $13.12 per hour [42] and the supervisor labor cost was calculated as 10% of the operating labor cost. Utility cost was taken as the output value from the economic report generated by the modeling simulation. Maintenance and repairs costs were estimated as 2% of the total project investment (TPI). The variable costs subtotal was the sum of all direct operating expenses. The standard electrical power cost was taken as $0.058/kW-h, by observing the electricity price for the Iowa industrial sector [43].

Fixed costs included overhead, local taxes, and insurances, with overhead taken as 50% of the sum of operating labor, supervision, and maintenance and repairs; local taxes were 1% of TPI; and the insurance cost was calculated based on 0.4% of TPI. The annual capital charges represent the annual payment of interest and principal on loan for total capital, calculated according to Equation (2) [40].

$$Annual\ Capital\ Charges\left(\frac{\$}{y}\right) = C_{TPI} i(1+i)^n/[(1+i)^n - 1] \quad (2)$$

where: C_{TPI} – loan of capital (in the form of TPI); i - annual interest rate of the loan (expressed as a decimal fraction); n - the payment period of the loan (years).

Annual operating costs are the sum of direct costs, indirect costs, and annual capital charges, while the product cost represents the annual operating cost divided by the annual production output [40]. The production cost of each coproduct (DDGS, DWGS, and corn oil) was calculated for both scenarios.

Fixed capital estimate summary, a process summary, and profitability analysis are the most important outputs from the model, pointing out that the unit production cost and unit production revenue are the most significant results of the profitability analysis.

To estimate the profitability of each scenario, the profit/loss values were determined by calculating the difference between the gross income and the total costs (Equation (3)). For each coproduct, considering each scenario of production, the gross profit was estimated by assuming the sale price, equal to the [41] market price multiplied by the production volume, and the total costs were taken as the sum of total variable costs and total fixed costs.

$$Profit/Loss\left(\frac{\$}{y}\right) = Gross\ Income - Total\ Costs \quad (3)$$

The disposal of whole stillage from a corn-based ethanol plant at a wastewater treatment plant was also considered. To conduct those calculations, some assumptions were made, such as choosing the Des Moines Metropolitan Wastewater Reclamation Authority (WRA) as the location for stillage disposal. Carbonaceous biochemical oxygen demand (CBOD), total suspended solids (TSS), and total Kjeldahl nitrogen (TKN) were considered to be the most likely pollutants. According to the WRA, the pollutants rate can be calculated using Equation (4). Pollutant costs were assumed to be consistent with WRA values (CBOD equal to $0.11/lb, TSS equal to $0.16/lb, and TKN equal to $0.61/lb). Other assumptions were that the whole stillage was to be disposed of at the wastewater treatment plant at the rate of 2000 ton/d, 1 lb of carbohydrates equated 0.9 lb of CBOD, the whole stillage TSS was equal to 25%, and the whole stillage TKN was 5,300 mg/L [44].

$$Pollutant\ rate\left(\frac{lb}{d}\right) = Pollutant\ \left(\frac{mg}{L}\right) \cdot 8.34 \cdot Volume\ (MGD) \quad (4)$$

where: MGD is million gallons per day.

To evaluate the economic assessment, both the conventional system and flocculation system were tested through a sensitivity analysis that varied the price of variable cost, fixed cost, and raw materials (whole stillage and chicken blood flocculants) cost, one at a time, from –30% to +30%, and DDGS, DWGS, and corn oil prices one at a time over the market price range. Sensitivity analyses are commonly used to identify which process parameters have the most impact on the overall economics of the process when costs and selling prices related to the evaluated parameters fluctuate under economic and market conditions [42,45].

For conducting a life cycle assessment (LCA), the outputs from the SuperPro model related to energy sources were used to calculate the carbon dioxide equivalent for each scenario by using a Greenhouse Gas Equivalencies Calculator [46] and an emission conversion factor for greenhouse gas inventories [47]. The environmental impact of DDGS, DWGS, and corn oil production processes were considered. The LCA inventory includes detailed input and output amounts of substances. Additionally, the Global Warming Potential (GWP) generated for each scenario, conventional system and flocculation system, in $kgCO_{2eq}/kWh$, was determined by comparing different energy sources (coal, gas, biomass, geothermal, hydropower, nuclear, solar power, and wind).

9. Results and Discussion

Capital costs, the initial investments in the facility, were developed from the costs of individual equipment items, instrumentation and control, process piping, insulation/electrical work, engineering/construction costs, yard improvements, and services facilities. The capital costs for both scenarios are shown in Figure 3. The costs per year related to the equipment values were provided in 2019 dollars.

Figure 3 shows that the overall fixed costs for Scenario I were about 10% lower than the overall fixed costs of Scenario II because of the flocculation system cost in Scenario II. The calculated ratio of the overall fixed costs for the flocculation system versus an evaporation system was determined to be 1.10 for each parameter considered that contributed to the overall capital costs. Although the evaporator, used in Scenario I, is considered an expensive piece of equipment, the flocculation process actually requires more equipment such as a flotation tank, a heat exchanger, and a filter instead of the evaporator. The costs related to the equipment in Scenario II were 20% more than those of the conventional system (Table 3). The 20% difference between the equipment costs of the two scenarios was calculated by the differences in the evaporation and flocculation equipment.

Table 3. Equipment costs for conventional ethanol production (Scenario I) and flocculation system (Scenario II).

Scenario I		**Scenario II**	
Equipment	**Unit Cost ($)**	**Equipment**	**Unit Cost ($)**
Blending tank	251,000	Blending tank	251,000
Blending tank	236,000	Blending tank	236,000
Component Splitter	458,000	Component Splitter	464,000
Rotary Dryer	1,131,000	Rotary Dryer	1,163,000
Flow Splitter	100,000	Flow Splitter	100,000
Decanter Centrifuge	230,000	Decanter Centrifuge	230,000
Evaporator	1,265,000	Flotation Tank	722,000
Unlisted Equipment*	918,000	Plate and Frame Filter	846,000
		Heat Exchanger	14,000
		Unlisted Equipment*	1,007,000
TOTAL	**4,589,000**	**TOTAL**	**5,033,000**

*Unlisted equipment accounts for other secondary equipment that is not considered explicitly in the model.

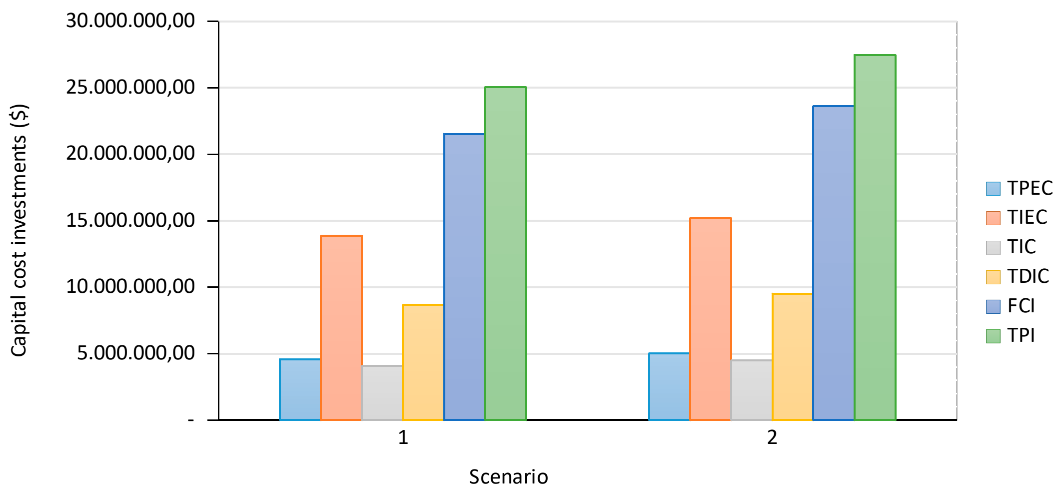

Figure 3. Overall fixed capital costs for Scenario I (evaporation process) and Scenario II (flocculation process. TPEC—Total Purchased Equipment Cost; TIEC—Total Installed Equipment Cost; TIC—Total Indirect Cost; TDIC—Total Direct and Indirect Costs; FCI—Fixed Capital Investment; and TPI—Total Project Investment).

The total purchased equipment cost (TPEC) was $4,589,000 for Scenario I and $5,033,000 for Scenario II; the Total Project Investment (TPI) for Scenario I was $25,036,700, while that for Scenario II was $27,459,100. Considering the evaporator cost and the unlisted equipment cost for Scenario I, and the flotation tank cost, the filter cost, the heat exchanger cost, and the unlisted equipment cost for Scenario II, it can be observed that the cited equipment costs for Scenario I are about 85% of the listed equipment costs for Scenario II.

The annual operating costs for both scenarios can be seen in Figure 4; they reflect the impact of the expenses associated with the facilities, labor, materials, and utility required for operation process on the overall annual operating cost.

Figure 4 shows that the material and facility costs had a substantial impact on the overall annual operating costs, followed by utility costs and labor costs for both scenarios. In Scenario II, material costs represented 44.5% of annual operating costs, while in Scenario I it was around 32%. For both models, the largest amount of material used was whole stillage, while for Scenario II, the CKB blood flocculants reflected an additional material cost. Wood et al. [15] reported similar annual operating costs results by analyzing 12 different scenarios of a TEA that considered a corn-based ethanol plant in 2011–12. Facility costs accounted for 45% and 40% of the annual operating costs for Scenario II and Scenario I, respectively.

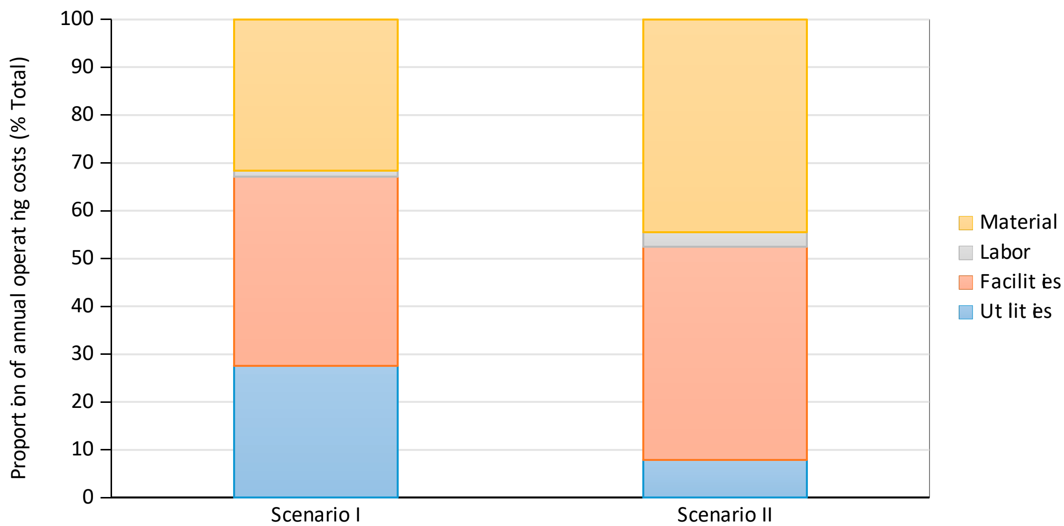

Figure 4. Proportion of annual operating costs for Scenario I (evaporation process) and Scenario II (flocculation process).

Besides material and facility costs, utility costs had the greatest impact on the overall annual costs of the facilities, especially for Scenario I. In the models, utility costs indicated the costs related to cooling/chilled water, steam, and electricity (Figure 5).

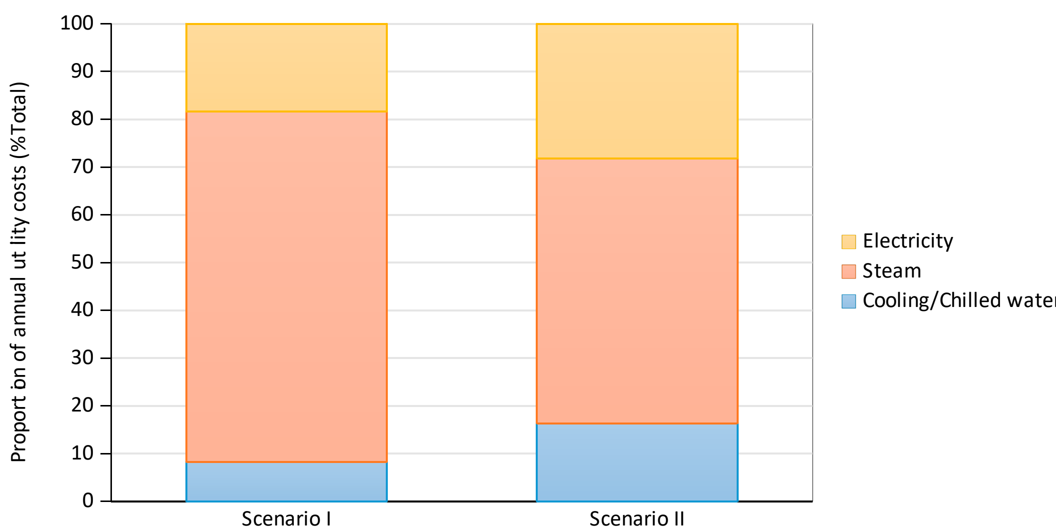

Figure 5. Proportion of annual utility costs for Scenario I (evaporation process) and Scenario II (flocculation process).

For Scenario I, steam had the most significant impact on the overall utility costs, representing almost 73% of total utility costs, followed by electricity (18%); for Scenario II, steam accounted for about 55% and electricity about 28% of utility expenses. Cooling/chilled water had the least overall impact in both scenarios, contributing about 8% and 16% for Scenario I and Scenario II, respectively.

The evaporator was responsible for the most substantial power consumption in Scenario I, while the dryer had the most significant impact on the annual utility costs in Scenario II. This may be related to the high moisture content of the input stream into the dryer under Scenario II conditions, which did not occur in Scenario I.

The total amount of main product and coproduct produced from Scenarios I and II can be observed in Table 4. The main product was Dried Distillers' Grains with Solubles (DDGS), and the coproducts were Wet Distillers' Grains with Solubles (DWGS) and corn oil.

Table 4 shows that the total production of DWGS and corn oil were about the same for both scenarios, with a slightly higher production of DWGS in the flocculation process, while conventional corn-based ethanol production resulted in a corn oil production that was slightly higher than in the flocculation system. However, the DDGS production from the flocculation scenario was lower than that from the conventional system.

Table 4. Total coproducts produced from the ethanol plant considering the conventional ethanol production (Scenario I) and the flocculation system (Scenario II).

	Coproduct	**Mass (t/y)**
Scenario I	DDGS	10,240.64
	DWGS	42,516.38
	Corn Oil	883.63
Scenario II	DDGS	8,041.57
	DWGS	42,691.81
	Corn Oil	848.63

Note: DDGS: Distillers' Dried Grains with Solubles; DWGS: Distillers' Wet Grains with Solubles.

DWGS production for Scenario II contributed almost 83% of the total output, while in Scenario I it represented 79% of the total production. In Scenario I, DDGS production was equal to 19% of the total, while in Scenario II it was about 16% of the total output. For both scenarios, corn oil contributed nearly 2% of the total production.

For both scenarios, the annual revenue was determined as the income received from the sale of the main product and the coproducts. DDGS is commonly used for feeding animals, and the market value is generally determined based on its protein content. According to the USDA Daily Ethanol Report of January 2019, the selling price of DDGS in Iowa-Western was an average of $150.00/t and the average selling price of DWGS was $40.00/t. Corn oil is known to represent the most significant market price compared to other coproducts from the ethanol facility. The USDA Daily Ethanol Report of January 2019 stated that the selling price for corn oil was $0.245 per pound, corresponding to $544.44/t. Therefore, by assuming the [41,48] prices to be the market prices for these products, the profit/loss was as in Figure 6a.

Results show that gross income related to the product sales and total costs were higher for Scenario I ($3,717,900 and $7,967,300) than for Scenario II ($3,376,000 and $7,106,200). Furthermore, none of the scenarios were profitable because of the high production cost, and low production and market price of DDGS, DWGS, and corn oil, for the given modeling conditions. Ratios of the gross income, total costs, and profit/loss for comparing the flocculation system to the evaporation system were determined and had values of about 0.9, meaning that the flocculation system (Scenario II) represented the best scenario for these assumed parameters (Figure 6b). The losses for the conventional system were higher than the losses for the flocculation system by a magnitude of 12%.

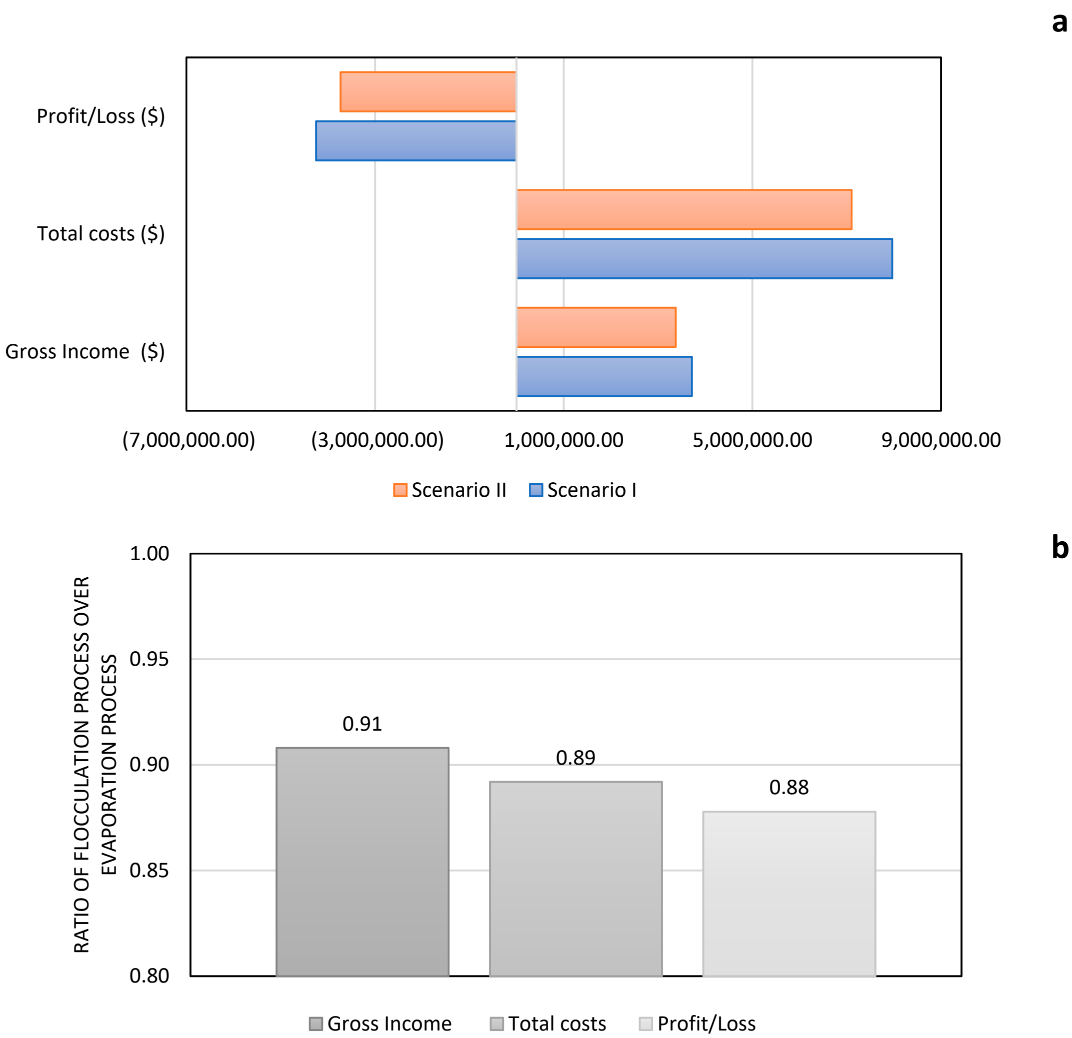

Figure 6. (**a**) Profitability of an ethanol plant, considering conventional ethanol production (Scenario I) and a flocculation system (Scenario II). The numbers between parentheses are negative. (**b**) Ratio of the profitability of Scenario II to Scenario I.

Flocculation systems are not widely used in ethanol production, but have recently been developed to provide additional value and efficiency to the production of ethanol coproducts. Harvesting Technology LLC, a U.S. company involved in ethanol production, has recently begun exploring this alternative technology to eliminate the high maintenance and power consumption associated with centrifuges for extracting corn distillers' grain and thin stillage. Moreover, the company uses dissolved air flotation (DAF) and a tricanter to separate the remaining solids and liquids. The company named the developed systems the CoProMax™ Process [49]. No information is available about the economic and environmental impacts of that technology applied on an industrial scale.

Since both simulated scenarios did not reflect profitability, the alternative of disposing the whole stillage from a corn-based ethanol plant at Des Moines Metropolitan Wastewater Reclamation Authority (WRA) was considered. The total cost of that process was calculated as $30.8 million/y, with the TSS and CBOD pollutant costs representing 86% and 12% of the total costs, respectively. While the stillage handling process for producing DDGS, DWGS, and corn oil is considered one of the major limitations of corn ethanol plants, based on the results of this study, the stillage process may be a cheaper solution to using corn ethanol plant residues rather than disposal of the whole stillage in a wastewater treatment plant.

A sensitivity analysis shows that variable cost is the parameter with the most significant sensitivity for both the conventional system and the flocculation system (Figures 7 and 8). The raw material prices (whole stillage and chicken blood flocculants) may be the main underlying reason for the variable cost sensitivity impact in both scenarios. In addition to variable cost and raw materials cost, the output market price for DWGS is a highly sensitive parameter, and the output market price for corn oil represents the least sensitivity for the two scenarios. Brown and Brown [40] stated that feedstock cost, process yield, and output market value are parameters commonly reported to be highly sensitive.

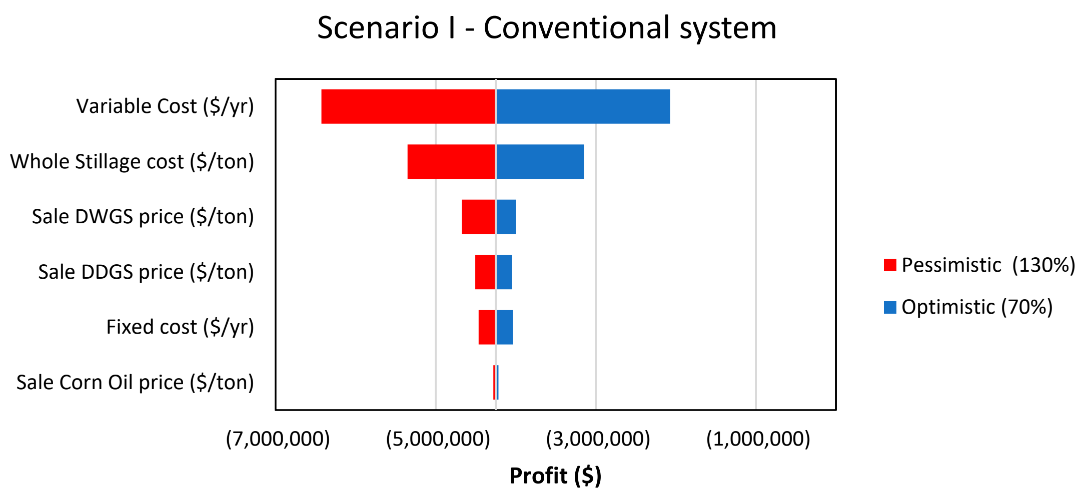

Figure 7. Sensitivity analyses of conventional system as a function of DDGS, DWGS, and corn oil prices from –30% (pessimistic case) to +30% (optimistic).

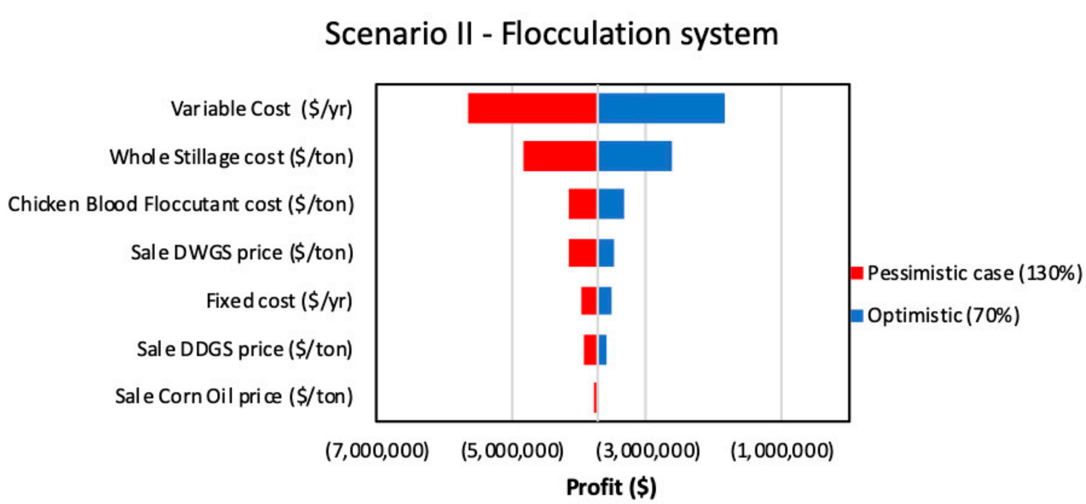

Figure 8. Sensitivity analyses of flocculation system as a function of DDGS, DWGS, and corn oil prices from –30% (pessimistic case) to +30% (optimistic).

The raw materials cost significantly affected the production cost of DDGS, DWGS, and corn oil, resulting in a direct increase in the cost of production when the price of feedstock increases, and greatly impacting system profitability.

Life cycle assessment (LCA) based on the life cycle inventory was performed to quantify the magnitude of the environmental impact for Scenarios I and II. Greenhouse gas emissions (GHG) were calculated by using the greenhouse gas equivalencies calculator [46] and the emission conversion factor for greenhouse gas inventories [47] Scenario I presented a higher amount of greenhouse gas emissions, with 63 $kgCO_{2eq}$/t of whole stillage processed as opposed to Scenario II, which presented 16 $kgCO_{2eq}$/t of whole stillage processed for the overall process.

Collotta et al. [50] evaluated the environmental impact of the two scenarios based on the application of two different microalgae harvesting technologies for biofuel production. The first scenario considered flocculation and centrifugation, while the second used direct centrifugation (without flocculation). Their results showed that using flocculation technology resulted in the lowest impact in almost all of the impact categories analyzed, except for agricultural land occupation and natural land transformation.

Additionally, a comparison of the GWP emissions from a variety of electrical sources was also performed using the life cycle emissions factor [47] Figure 9a shows the emissions for different sources used to generate electricity, showing that coal, nuclear power, hydropower, natural gas, and oil are most typically used to generate electricity [51].

Not only the energy cost but also the scarcity or emissions may affect the energy source decision. From Figure 9a, it can be observed that emissions follow the same trend in both scenarios, showing onshore wind to be the electric source with lower emissions impact than the other sources, followed by offshore wind, nuclear, hydropower, concentrated solar power, and geothermal. On the other hand, coal had the greatest impact on the environment, with the highest emissions level for the two scenarios (Table 5).

Table 5. Emissions from a variety of electricity supply technologies for the conventional system (Scenario I) and flocculation system (Scenario II).

	Scenario I	**Scenario II**
Electricity source	**$kgCO_{2eq}$/kWh**	**$kgCO_{2eq}$/kWh**
Coal—PC	4157	1778
Gas—Combined Cycle	2484	1063
Biomass—cofiring	3752	1605
Biomass—dedicated	1166	499
Geothermal	193	82
Hydropower	122	52
Nuclear	61	26
Concentrated Solar Power	137	59
Solar PV—rooftop	208	89
Solar PV—utility	243	104
Wind onshore	56	24
Wind offshore	61	26
Average of GWP considering all electricity sources	1053	451

Note: PC: Pulverized Coal; PV: Photovoltaic; GWP: Global warming potential.

The average GWP emissions, considering all electricity supply technologies listed for the conventional system, was 0.002 $kgCO_{2eq}$/kWh, while the flocculation system presented an average of 0.001 $kgCO_{2eq}$/kWh. The flocculation system presented the lowest emissions of all the electricity sources analyzed, about 43% of the total emissions from each electricity source compared to the conventional system (Figure 9b).

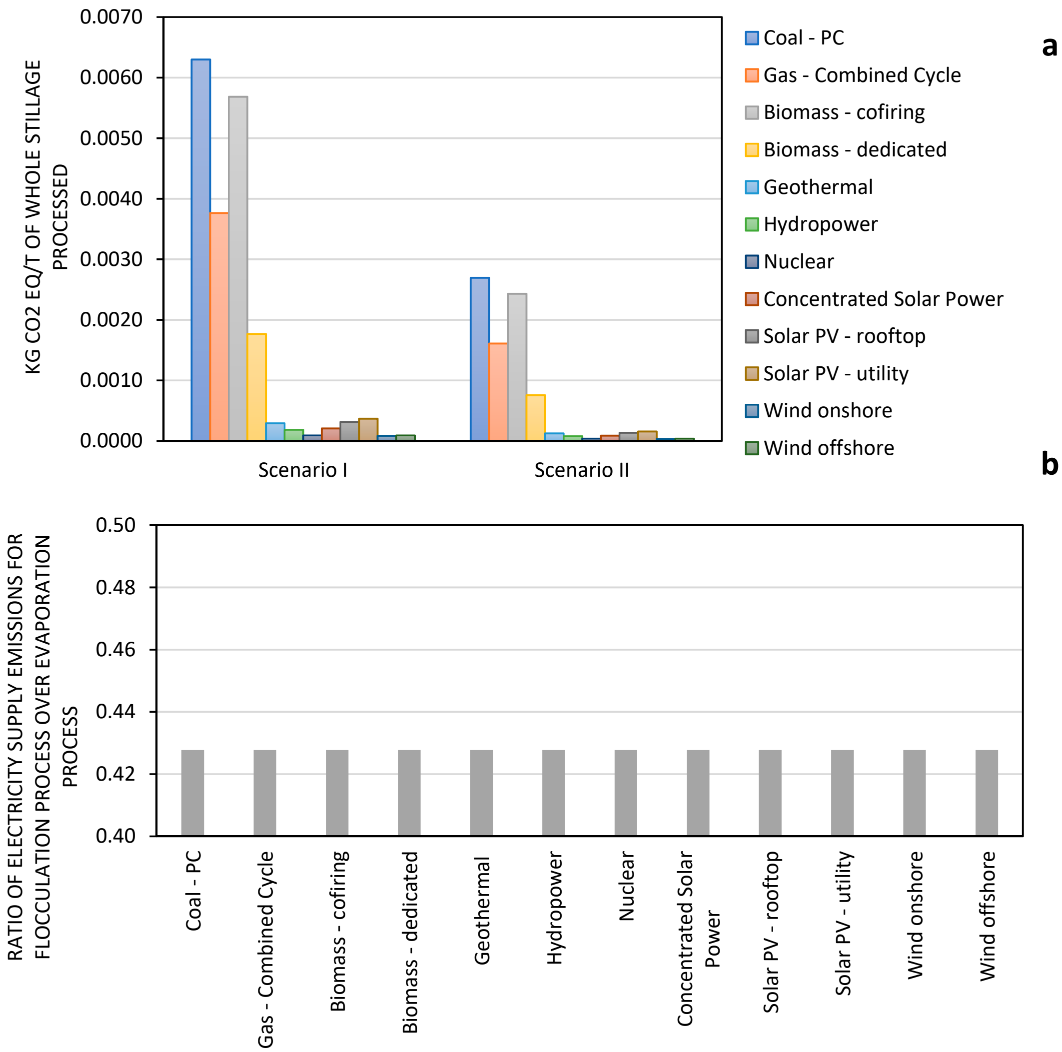

Figure 9. (**a**) Global Warming Potential (GWP) emissions in $kgCO_{2eq}$/t of whole stillage processed for the conventional system (Scenario I) and flocculation system (Scenario II) using different electricity supply technologies. (**b**) Ratio of the GWP emissions in $kgCO_{2eq}$/t of whole stillage processed for the conventional system (Scenario I) and flocculation system (Scenario II) using different electricity supply technologies.

10. Conclusions

The flocculation system (Scenario II), simulated as a substitute for an evaporation system in a conventional corn-based ethanol plant (Scenario I), can be an alternative system for minimizing the amount of energy consumed during DDGS, DWGS, and corn oil production, because it presents a significantly lower utility cost compared to a conventional system, and represents less than 28% of the utility cost of Scenario I. However, both the overall fixed costs and the annual operating costs for Scenario II were higher than those for Scenario I. Even though the evaporator is considered expensive equipment, Scenario I presented a total project investment about 10% lower than Scenario II due to the need for more equipment for the flocculation system. Additionally, both scenarios reflected negative profit, and from a sensitivity analysis it could be concluded that the feedstocks cost substantially impacted the DDGS, DWGS, and corn oil production cost.

With respect to environmental aspects, the LCA results show that the flocculation system presented the lowest GWP emissions among the several electricity supply technologies analyzed.

Scenario II presented a major reduction of CO_2 equivalent emissions, about 57% lower than the conventional system.

Author Contributions: M.C.T.B. O. built the model and drafted the paper. K.A.R. conceived the project, verified the results, and edited the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kadhum, H.J.; Rajendran, K.; Murthy, G.S. Effect of solids loading on ethanol production: Experimental, Economic and Environmental analysis. *Bioresour. Technol*. **2017**, *244*, 108–116.
2. Garcia, C.A.; Manzini, F.; Islas, J.M. Sustainability assessment of ethanol production from two crops in Mexico. *Renew. Sustain. Energy Rev.* **2017**, *72*, 1199–1207.
3. Ghadiryanfar, M.; Rosentrater, K.A.; Keyhani, A.; Omid, M. A review of macroalgae production, with potential applications in biofuels and bioenergy. *Renew. Sustain. Energy Rev.* **2016**, *54*, 473–481.
4. Goldemberg, J.; Coelho, S.T.; Guardabassi, P. The sustainability of ethanol production from sugarcane. *Energy Policy* **2008**, *36*, 2086–2097.
5. Izmirlioglu, G.; Demirci, A. Ethanol production in biofilm reactors from potato waste hydrolysate and optimization of growth parameters for Saccharomyces cerevisiae. *Fuel* **2016**, *181*, 643–651.
6. Nguyen, T.L.T.; Gheewala, S.H.; Garivait, S. Full chain energy analysis of fuel ethanol from cane molasses in Thailand. *Appl. Energy* **2008**, *85*, 722–734.
7. Gnansounou, E.; Dauriat, A.; Villegas, J.; Panichelli, L. Life cycle assessment of biofuels: Energy and greenhouse gas balances. *Bioresour. Technol.* **2009**, *100*, 4919–4930.
8. Ometto, A.R.; Hauschild, M.Z.; Roma, W.N.L. Lifecycle assessment of fuel ethanol from sugarcane in Brazil. *Int. J. Life Cycle Assess*. **2009**, *14*, 236–247.
9. Melamu, R.; Von Blottnitz, H. 2nd Generation biofuels a sure bet? A life cycle assessment of how things could go wrong. *J. Clean. Prod*. **2011**, *19*, 138–144.
10. Patel, M.; Zhang, X.; Kumar, A. Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review. Renew. Sustain. *Energy Rev*. **2016**, *53*, 1486–1499.
11. Mandegari, M.A.; Farzad, S.; Görgens, J.F. Economic and environmental assessment of cellulosic ethanol production scenarios annexed to a typical sugar mill. *Bioresour. Technol*. **2017**, *224*, 314–326.
12. Contreras, A.M.; Rosa, E.; Pérez, M.; Van Langenhove, H.; Dewulf, J. Comparative life cycle assessment of four alternatives for using by-products of cane sugar production. *J. Clean. Prod.* **2009**, *17*, 772–779.
13. Aydiner, C.; Sen, U.; Topcu, S.; Ekinci, D.; Altinay, A.D.; Koseoglu-Imer, D.Y.; Keskinler, B. Techno-economic viability of innovative membrane systems in water and mass recovery from dairy wastewater. *J. Membr. Sci.* **2014**, *458*, 66–75.
14. Ganesan, V.; Rosentrater, K.A.; Muthukumarappan, K. Flowability and handling characteristics of bulk solids and powders–A review with implications for DDGS. *Biosyst. Eng.* **2008**, *101*, 425–435.
15. Wood, C.; Rosentrater, K.A.; Muthukumarappan, K. Techno-economic modeling of a corn based ethanol plant in 2011/2012. *Ind. Crop. Prod*. **2014**, *56*, 145–155.
16. Singh, V.; Rausch, K.D.; Yang, P.; Shapouri, H.; Belyea, R.L.; Tumbleson, M.E. Modified Dry Grind Ethanol Process; Departments of Agricultural Engineering, University of Illinois at Champaign-Urbana, UILU: Champaign, IL, USA, 2001.
17. Rosentrater, K.A.; Muthukumarappan, K. Corn ethanol coproducts: Generation, properties, and future prospects. *Int. Sugar J*. **2006**, *108*, 648–657.
18. Rosentrater, K.A. Production and Use of Evolving Corn-Based Fuel Ethanol Coproducts in the US. In Biofuels-Status and Perspective; InTech: Rijeka, Croatia, 2015.
19. Pimentel, D.; Patzek, T.W. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. *Nat. Resour. Res*. **2005**, *14*, 65–76.
20. Shan, L.; Liu, J.; Ambuchi, J.J.; Yu, Y.; Huang, L.; Feng, Y. Investigation on decolorization of biologically pretreated cellulosic ethanol wastewater by electrochemical method. *Chem. Eng. J*. **2017**, *323*, 455–464.
21. Zhu, X.; Li, M.; Zheng, W.; Liu, R.; Chen, L. Performance and microbial community of a membrane bioreactor system–Treating wastewater from ethanol fermentation of food waste. *J. Environ. Sci*. **2017**, *53*, 284–292.

22. Baral, N.R.; Wituszynski, D.M.; Martin, J.F.; Shah, A. Sustainability assessment of cellulosic biorefinery stillage utilization methods using emergy analysis. *Energy* **2016**, *109*, 13–28.
23. Trinh, T.N.; Jensen, P.A.; Sárossy, Z.; Dam-Johansen, K.; Knudsen, N.O.; Sørensen, H.R.; Egsgaard, H. Fast pyrolysis of lignin using a pyrolysis centrifuge reactor. *Energy Fuels* **2013**, *27*, 3802–3810.
24. Eldien, W.N.; Moawia, M.; Mahgoub, M.; Badawi, E.; Eltahir, E. Simulation of Surface Drinking Water Treatment Plant. International Journal of Trend in Research and Development, **2017**, *4*, 421–427.
25. Zhao, G.; Ji, S.; Sun, T.; Ma, F.; Chen, Z. Production of Bioflocculants Prepared from Wastewater Supernatant of Anaerobic Co-Digestion of Corn Straw and Molasses Wastewater Treatment. *BioResources* **2017**, *12*, 1991–2003.
26. Nguyen, V.H.; Klai, N.; Nguyen, T.D.; Tyagi, R.D. Impact of extraction methods on bio-flocculants recovered from backwashed sludge of bio-filtration unit. *J. Environ. Manag*. **2016**, *180*, 344–350.
27. Piazza, G.J.; McAloon, A.J.; Garcia, R.A. A renewable flocculant from a poultry slaughterhouse waste and preliminary estimate of production costs. Resour. *Conserv. Recycl*. **2011**, *55*, 842–848.
28. Hameed, Y.T.; Idris, A.; Hussain, S.A.; Abdullah, N. A tannin-based agent for coagulation and flocculation of municipal wastewater: Chemical composition, performance assessment compared to Polyaluminum chloride, and application in a pilot plant. *J. Environ. Manag*. **2016**, *184*, 494–503.
29. Piazza, G.J.; Garcia, R.A. Meat & bone meal extract and gelatin as renewable flocculants. *Bioresour. Technol*. **2010**, *101*, 781–787.
30. Piazza, G.J.; Garcia, R.A. Proteins and peptides as renewable flocculants. *Bioresour. Technol*. **2010**, *101*, 5759–5766.
31. Balan, V.; Chiaramonti, D.; Kumar, S. Review of US and EU initiatives toward development, demonstration, and commercialization of lignocellulosic biofuels. *Biofuels Bioprod. Biorefining* **2013**, *7*, 732–759.
32. Chum, H.L.; Warner, E.; Seabra, J.E.; Macedo, I.C. A comparison of commercial ethanol production systems from Brazilian sugarcane and US corn. *Biofuels Bioprod. Biorefining* **2014**, *8*, 205–223.
33. Guinée, J.B.; Heijungs, R.; de Haes, H.A.U.; Huppes, G. Quantitative life cycle assessment of products: 2. Classification, valuation and improvement analysis. *J. Clean. Prod.* **1993**, *1*, 81–91.
34. Simba, F.; Trojer, L.; Mwinyiwiwa, B.; Mvungi, N.; Mjema, E. Techno-economic analysis of UMTS900 and UMTS2100 for rural connectivity in Tanzania. In 2012 IEEE 14th International Conference on Communication Technology; IEEE: Piscataway, NJ, USA, November 2012; pp. 10–15.
35. Budzinski, M.; Nitzsche, R. Comparative economic and environmental assessment of four beech wood based biorefinery concepts. *Bioresour. Technol.* **2016**, *216*, 613–621.
36. Kwiatkowski, J.R.; McAloon, A.J.; Taylor, F.; Johnston, D.B. Modeling the process and costs of fuel ethanol production by the corn dry-grind process. *Ind. Crop. Prod*. **2006**, *23*, 288–296.
37. Dutta, A.; Talmadge, M.; Hensley, J.; Worley, M.; Dudgeon, D.; Barton, D.; Wright, C.T. Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol: Thermochemical Pathway by Indirect Gasification and Mixed Alcohol Synthesis; No. NREL/TP-5100-51400; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2011.
38. Larson, E.M.; Stock, R.A.; Klopfenstein, T.J.; Sindt, M.H.; Huffman, R.P. Feeding value of wet distillers byproducts for finishing ruminants. *J. Anim. Sci*. **1993**, *71*, 2228–2236.
39. Del Rio De Reys, M.T.E.; Constantinides, S.M.; Sgarbieri, V.C.; El-Dash, A.A. Chicken blood plasma proteins: Physicochemical, nutritional and functional properties. *J. Food Sci.* **1980**, *45*, 17–20.
40. Brown, R.C.; Brown, T.R. *Biorenewable Resources: Engineering New Products from Agriculture*; John Wiley & Sons: Hoboken, NJ, USA, 2013.
41. United States Department of Agriculture (USDA). Daily Ethanol Report. Agricultural Marketing Service. Livestock, Poultry & Grain Market News. 2019. Available online: https://www.ams.usda.gov/mnreports/lsdethanol.pdf (accessed on 12 February 2019).
42. Cheng, M.H. Sustainability Analysis of Soybean Refinery: Soybean Oil Extraction Process. Ph.D.Thesis, Iowa State University, Ames, IA, USA, 2017.
43. EIA. U.S. Energy Information Administration. Independent Statistics & Analysis. Electric Power Monthly. 2018. Available online: https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a (accessed on 17 January 2019).
44. Eskicioglu, C.; Kennedy, K.J.; Marin, J.; Strehler, B. Anaerobic digestion of whole stillage from dry-grind corn ethanol plant under mesophilic and thermophilic conditions. *Bioresour. Technol.* **2011**, *102*, 1079–1086.
45. Aden, A.; Foust, T. Technoeconomic analysis of the dilute sulfuric acid and enzymatic hydrolysis process for the conversion of corn stover to ethanol. *Cellulose* **2009**, *16*, 535–545.

46. United States Environmental Protection Agency (EPA). Energy and the Environment. Greenhouse Gas Equivalencies Calculator. Available online: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator (accessed on 21 November 2018).
47. EPA, U. Emission factors for greenhouse gas inventories. In *Stationary Combustion Emission Factors*; US Environmental Protection Agency: Washington, DC, USA, 2018.
48. United States Department of Agriculture (USDA). National Agricultural Statistics Service. 2018. Available online: https://www.nass.usda.gov/Charts_and_Maps/Agricultural_Prices/pricecn.php (accessed on 17 January 2019).
49. Bolton, G.; Jepson, C. CoProMax™ Process: Bringing Additional Value and Efficiency to Ethanol Coproduct Production. [PDF File]. 2018. Available online: http://harvestingtech.com/wordpress/wp-content/uploads/1949/06/12-page-CoProMax-PPT-3.17.pdf (accessed on 1 May 2019).
50. Collotta, M.; Champagne, P.; Mabee, W.; Tomasoni, G.; Leite, G.B.; Busi, L.; Alberti, M. Comparative LCA of Flocculation for the Harvesting of Microalgae for Biofuels Production. *Procedia CIRP* **2017**, *61*, 756–760.
51. Scientific Applications International Corporation (SAIC); Curran, M.A. Life-Cycle Assessment: Principles and Practice; National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency: Cincinnati, OH, USA, 2006; pp. 1–80.