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Cost and Environmental Benefits of Using Pelleted Corn Stover for Bioethanol Production

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Abstract: While the production costs and logistical benefits of biomass pelleting have been widely discussed in the literature, the downstream economic and environmental benefits of processing pelleted biomass have been largely neglected. To investigate those benefits, we performed a comparative techno-economic analysis and life cycle assessment of producing ethanol using loose and pelleted forms of biomass. Analyses of a 2000 metric tons (dry)/d biorefinery showed that using pelleted biomass is more economical than using loose or baled biomass. The lowest minimum ethanol selling price (MESP) for pelleted biomass was USD 0.58/gal less than the lowest MESP for loose biomass. Among all processing conditions analyzed, MESP for ethanol produced with pelleted biomass was always lower than when produced with loose biomass. Shorter pretreatment and hydrolysis times, higher pretreatment solids loadings, lower ammonia requirements, and reduced enzyme loadings were the primary factors contributing to lower MESP with pelleted biomass. Similarly, pelleted biomass also demonstrated a 50% lower life cycle greenhouse gas emission compared to loose biomass. Emissions from higher pelleting energy were offset by downstream advantage in lower chemical needs.

Keywords: techno-economic analysis; life cycle analysis; cellulosic biorefinery; biomass pellets; soaking in aqueous ammonia pretreatment

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1. Introduction

Following the Renewable Fuel Standards (RFSs) [1] and Energy Security Act of 2007 [2], biofuels including ethanol have been increasingly produced and used in blending with gasoline in the US. Although the majority of ethanol currently blended with gasoline in the US is starch-based, second-generation biofuels that promise better environmental performance through reduced greenhouse gas emissions and are made from lignocellulosic biomass continue to be pursued [3]. Compared to a broad range of biomass sources, lignocellulosic biomass offers additional benefits due to its potentially wider availability and lower cost. However, the production cost of cellulosic ethanol is currently high compared to that of corn ethanol and gasoline.

Biomass is inherently bulky and recalcitrant to microbial degradation, both of which contribute to the challenge of economical cellulosic biofuel production. Biomass densification through pelletization is an option to improve handling, transportation, and storage costs [4]. The use of pelleted biomass also allows benefits in downstream processing within a biorefinery. Pelleted biomass has exhibited advantages in pretreatment and hydrolysis. The use of pelleted biomass allows reductions in pretreatment severity parameters such as time, temperature, and ammonia concentration [5]. It also enables the doubling of solid loadings during pretreatment, reducing reactor volume, energy, and ammonia requirements [6]. Enzyme loadings and hydrolysis time can also be reduced using pelleted biomass [7–10]. The tradeoffs between pretreatment and hydrolysis under low to high pretreatment severity and enzyme loadings for pelleted biomass were quantified by a previous study [5]. That study identified the least severe pretreatment conditions, lowest enzyme loadings, and shortest hydrolysis time needed to achieve 90% hydrolysis glucose yields for both loose and pelleted biomass. The effect of these changes in pretreatment and hydrolysis process conditions on the overall cost and greenhouse gas emissions of biofuel production has not been reported.

Techno-economic analysis (TEA) together with life cycle analysis (LCA), are powerful tools for analyzing the technical, economic, and environmental feasibility of processing technology. The concept of using TEA to determine the minimum ethanol selling price (MESP) has been repeatedly used by many including the Biomass Refining Consortium for Applied Fundamentals and Innovation (CAFI) project [11] and NREL to determine minimum ethanol selling price (MESP) for a range of feedstock pretreatments [12,13]. Several other studies have used the NREL model as a baseline to understand the economic competitiveness of cellulosic biofuels [14–17]. Those studies showed that final ethanol price is highly sensitive to feedstock and enzyme costs, pretreatment costs, and sugar conversions. Among the different pretreatment methods, dilute acid has shown to be the least expensive process [14,16]. However, none of those studies considered using pelleted biomass in their analyses within biorefinery, though some studies considered the use of pelleted biomass within the supply chain logistics framework [18–21]. Moreover, few other studies did an environmental impact analysis of a cellulosic biorefinery and showed that cellulosic biofuel performs better than a conventional fuel environmentally [22,23].

In this study, the use of both loose and pelleted biomass as processing feedstock is investigated. Process data is used from a previous study [5] to construct comparative TEA and LCA models based on the original NREL study [13] to compare between loose and pelleted biomass. The goal of this study is to determine how pretreatment benefits from pelletizing biomass translates to changes in the overall economic and environmental effects of producing ethanol. We estimate and compare both biorefinery operating and capital costs for producing ethanol using either pelleted or loose biomass. We then carry out sensitivity analyses to identify the effect of variations in selected input parameters on the final MESP of ethanol. Additionally, we estimate cradle to grave life cycle greenhouse gas emissions from producing ethanol from each biomass form and identify the hotspots.

2. Materials and Methods

We conduct TEA and LCA analyses for a 2000 MT/d capacity biorefinery. The data on biomass compositional analysis, pretreatment, and hydrolysis conditions are taken from a previous study [5]. The process is divided into a total of 8 different areas (Figure 1) including: Feedstock handling (Area 100); Pretreatment (Area 200); Hydrolysis and Fermentation (Area 300); Distillation, Dehydration, and Solids Separation (Area 400); Product Storage (Area 500); Waste Water Treatment (Area 600); Combustor/Turbogenerator (Area 700); and Utilities (Area 800). Each Area is briefly described in Section 2.2.

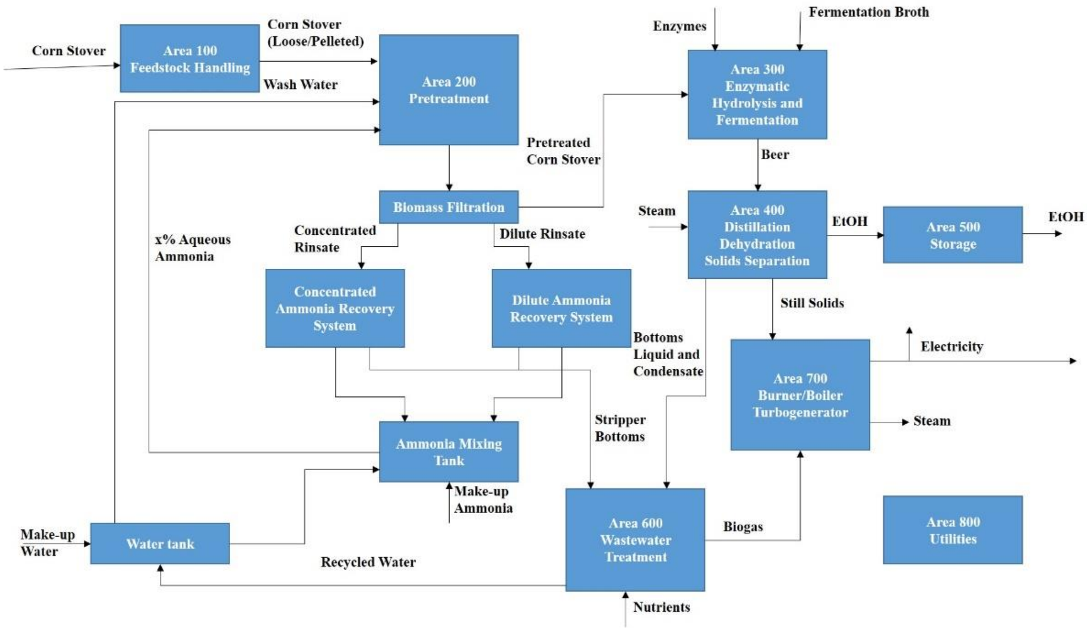

Figure 1. General process layout for cellulosic ethanol production from corn stover in a biorefinery.

2.1. Functional Unit and System Oundary

The system boundary for TEA includes all processes that take place within the biorefinery. We consider two scenarios of biofuel production that correspond to using either pelleted or loose biomass as the biorefinery feedstock. In both scenarios, ethanol is the primary output product of the biorefinery. Biogas, lignin and other residual biomass are burned to produce steam and electricity. Any extra electricity remaining after supplying energy to the plant is assumed to be sold to the grid.

The LCA study is performed following ISO standards [24]. The general principle of LCA includes defining the goal and scope of the study, inventory collection, impact assessment, and interpretation of the results. LCA is an iterative process and the results from it are subjective. The goal of this study is to compare the life cycle greenhouse gas emissions of ethanol production using loose and pelleted biomass. The functional unit in this study is selected as Megajoule (MJ) energy. The system boundary of the LCA model includes all the relevant processes including biomass production, transportation, preprocessing, biorefinery processing, biorefinery chemicals production, ethanol transportation, and ethanol burning. The extra electricity generated is modeled as an avoided product (system expansion). The transportation of biomass and ethanol is done by truck. The preprocessing step for loose biomass includes grinding, and for pelleted biomass includes grinding and pelleting.

2.2. Process Description

This section provides details for the processes demonstrated in Figure 1.

2.2.1. Feedstock Handling

Corn stover is used as the biorefinery feedstock. The radius for feedstock collection is assumed to be similar to the NREL study [13]. Depending on the scenario, corn stover is delivered either as pellets or bales. In the case of bales, fine grinding occurs onsite before further processing. Pellets can be used directly in the pretreatment process without any grinding. The feedstock costs for both pelleted and loose biomass are taken from a previous study [17]. Material handling costs in the biorefinery (Area 100 in Figure 1) are included with the feedstock price. The difference in cost of pelleted and loose biomass is USD 10 per metric ton. Other studies have suggested higher costs for pelleted biomass based on the technology they adopt [18].

2.2.2. Pretreatment

Soaking in aqueous ammonia (SAA) is the model pretreatment method used in this study (Area 200 in Figure 1). This alkaline pretreatment is effective in removing up to 80% of lignin and about 20% of hemicellulose [25] while retaining more than 95% of the cellulose. Aqueous ammonia (typically 12–16%) is used to soak the biomass for a specified time and temperature (Table 1).

Table 1. Pretreatment conditions modeled for loose and pelleted biomass scenarios (selected from [5]).

Treatment	Pretreatment Conditions		
	Temperature (°C)	**Time (h)**	**Ammonia Concentration (*w*/*v* %)**
PT1	45	9	12
PT2	50	14	14
PT3	55	19	16

The composition of corn stover used in calculations is taken from our previous study [5] (Table A1). The ash percentage for both forms of biomass is taken as 12% based on the laboratory results.

The majority of equipment and costs in Area 200 are adapted from NREL and scaled accordingly. Stainless steel reactors can be used for SAA pretreatment, while dilute acid pretreatment requires the more expensive Incoloy 825 alloy to withstand acid corrosiveness. Pretreatment reactors in this study are assumed to be similar to the ethanol storage tank with 40% higher costs to accommodate for material handling modifications [26]. Reactor downtime is assumed to be 4 h in between the batches. The number of pretreatment reactors needed was calculated by dividing daily biomass throughput (MT/d) by reactor capacity (MT per reactor) and multiplying by pretreatment residence time and reactor downtime.

Ammonia used during pretreatment is recovered using two ammonia recovery systems (Figure A1 in Appendix A). After pretreatment, biomass is pressed to drain the liquid that goes to the concentrated ammonia recovery system. Process water is used to wash the biomass to bring the pH close to neutral, and then the biomass is pressed again. The diluted ammonia drained from the wash goes to the dilute ammonia recovery system. In the recovery units, ammonia is stripped using steam generated from the boiler in Area 700. It is assumed that 98% of ammonia can be recovered for reuse in pretreatment. The capital costs of the ammonia stripping section are adapted from a previous study [26].

Since there is no commercial facility available to get the exact wastewater requirements for SAA pretreatment, it is assumed that the system is similar to a multistage leaching process [27]. The volume of water required is assumed to be 26 L per kilogram of biomass. The capital cost for installing such a system is not included in this calculation. The solid loadings in the pretreatment reactor are assumed to be 10% for loose biomass and 20% for pelleted biomass [5,9].

2.2.3. Hydrolysis and Fermentation

Pretreated biomass is transferred to Area 300 (Figure 1), representing hydrolysis and fermentation. Hydrolysis and fermentation are done in batches with a single reactor used for both processes. The solids loading is assumed to be 10% for hydrolysis for both biomass forms. Although in the previous study [5], the solids loading used is 1% glucan loading (10 g/L) (equivalent to 2.5% solid loading), 10% would be reasonable for a commercial facility for a comparative purpose and based on what we had in the laboratory conditions. Previous studies have suggested that 18% and higher solids loading would be economical for a biorefinery [28,29]. However, the effect of this solids loading needs to be confirmed by further testing [15]. Enzymes are added based on the glucan content of the pretreated feedstock. A combination of 3 different enzymes (cellulase, cellobiase, and xylanase) is used. Enzymes are purchased from commercial vendors and a separate enzyme production unit is not included. Enzyme prices are taken from a previous study [30]. The equipment and costs are adapted from NREL and scaled accordingly [13]. In the base case scenario, 95% of glucose and 85% of xylose are assumed to be converted to ethanol, respectively. Hydrolysis and fermentation reactor downtime is assumed to be 12 h for reactor unloading, cleaning, and loading.

2.2.4. Distillation, Dehydration and Solids Separation

Equipment size and costs in the distillation section (Area 400) are adapted from NREL [13]. Distillation is done in two stages to concentrate fermented beer to 95% ethanol, and the remaining water is removed by molecular sieve adsorption. The solids remaining in the distillation column are filtered and sent to the combustor in Area 700. Ethanol recovered from this section is sent to the ethanol storage tanks.

2.2.5. Storage, Wastewater Treatment, Combustor and Utilities

Area 500, representing storage, is also adapted from the NREL study [13]. Equipment such as sulfuric acid tanks and pumps are not required for ammonia pretreatment and are not included in this analysis. The sizing and costs for other equipment are scaled according to the flow rates.

Wastewater treatment section is represented by Area 600. The equipment sizes and costs are scaled from NREL study [13] based on the flow of solids from the pretreatment section to the wastewater treatment area [26]. Wastewater treatment generates biogas and sludge that goes to the combustor. It is assumed that the water leaving this section is sufficiently clean to be used for all processes within the biorefinery.

Area 700 includes a combustor for biogas, residual lignin, slurry from wastewater treatment, and the biomass remaining from the distillation area. Area 800 represents the utilities section. The equipment sizes and costs for these areas are scaled from the NREL report based on flow rates specific to our study [13].

2.3. Process Conditions for Loose and Pelleted Biomass

Table 1 shows the pretreatment conditions considered in this study. Pretreatment parameters that are varied include temperature, time (treatment duration), and ammonia concentration.

Table 2 shows the hydrolysis and enzyme loading conditions used in the analysis for both biomass forms with equivalent xylose yields [5]. Low enzyme loadings refer to 5 Filter Paper Unit (FPU)/g glucan and 100 Xylanase Unit (XU)/g glucan. Similarly, medium and high enzyme loadings refer to 15 and 25 FPU/g glucan and 300 and 500 XU/g glucan, respectively. Cellobiase is included at a 1:1 ratio of FPU to CBU (Cellobiase Unit) for all loadings. These enzyme loadings conditions are chosen based on previous laboratory experiments and represent the time 90% glucose yields were reached with each form of biomass at different pretreatment severities and enzyme loadings [5]. Glucose yields of 90% were only reached with loose biomass at the highest enzyme loadings tested.

Table 2. Hydrolysis conditions used in this analysis for loose and pelleted forms of biomass scenarios (selected from [5]).

Treatments	Enzyme Loadings	Hydrolysis Time (h) to Achieve 90% Glucose Yields		Xylose Yields (%)	
		Loose Corn Stover	Pelleted Corn Stover	Loose Corn Stover	Pelleted Corn Stover
PT1	High	48	20	63	60
PT2	High	33	17	72	74
	Medium	-	23	-	73
PT3	High	17	17	59	66
	Medium	-	27	-	66
	Low	-	48	-	62

2.4. *Process Economics and Assumptions*

Table 3 provides the details of the assumptions for the TEA.

Table 3. Summary of assumptions made for discounted cash flow analysis.

Item	Unit
Working capital	5% of fixed capital investment
Depreciation period for general plant	7 years
Depreciation period for steam/electricity system	20 years
Construction period	3 years
Start-up time	0.25 years
Income tax rate	35%
Cost year for analysis	2017
Equity	40%
Loan interest	8%
Loan term	10 years
Project life	30 years

Operating Costs

The variable operating costs per unit basis are calculated based on 2017 USD (Table 4).

Table 4. Variable operating costs (2017 USD).

Item	Unit	Unit Cost (USD)
Loose corn stover [17]	MT	$95
Pelleted corn stover [17]	MT	$106
Anhydrous ammonia [13]	MT	$567
Corn steep liquor [13]	MT	$72
Enzyme protein cost [13]	Kg	$6
Diammonium phosphate (DAP) [13]	MT	$1247
Sorbitol [13]	MT	$1423
Wastewater treatment chemicals [26]	Kg	$529
Caustic [13]	MT	$189
Wastewater treatment polymers [26]	MT	$8537
Boiler chemicals [26]	MT	$6311
Flue-gas desulfurization (FGD) lime [13]	MT	$252
Ash disposal [13]	MT	$40
Cooling water chemicals [13]	MT	$3782
Make-up water [13]	MT	$0.32
Electricity [13]	kWh	$0.07

2.5. Sensitivity Analysis

A sensitivity analysis was conducted to determine the effect of input parameters on the minimum ethanol selling price (MESP). This analysis helps to determine which parameters have a greater influence on MESP so that future research can be guided to optimize those parameters. For sensitivity analyses, the processing conditions resulting in the lowest MESP for each form of biomass were selected.

2.6. Life Cycle Inventory and Life Cycle Assessment

Life cycle analysis was performed for the conditions that resulted in the lowest MESP. Therefore, PT2 (50 °C, 14 h, 14% ammonia) at high enzyme loadings and PT3 (55 °C, 19 h, 16% ammonia) at low enzyme loadings for loose and pelleted biomass respectively, were chosen. The mass flow rates for both loose and pelleted biomass cases are taken from Pandey et al. [5]. The emission data for biomass production, enzyme production, biorefinery chemicals, and truck transportation were taken from Ecoinvent 3 and USLCI databases. The energy required for biomass transportation was taken from Nahar et al. [6] and the energy required for pretreatment for each loose and pelleted case was calculated based on Mafe et al. [31]. The biomass carbon credit is calculated based on the carbon content of the corn stover feedstock used in the study. Similarly, the energy required for biomass preprocessing was taken from Kenney et al. [32]. The CO_2 emission from ethanol burning was calculated based on stoichiometry.

SimaPro v9.0 was used to perform life cycle analysis. A full cradle-to-grave life cycle impact assessment was done for a single issue in the IPCC GWP100a impact category.

3. Results and Discussion

The volume of ethanol produced from loose and pelleted biomass under different pretreatment conditions and enzyme loadings is given in Table 5. Although glucan hydrolysis was considered 90% for all cases, ethanol production varies due to differences in xylan hydrolysis and carbohydrate loss during pretreatment. Ethanol yield rates varied from 57 to 69 gallons of ethanol per metric ton of feedstock (Table 5).

Table 5. Annual ethanol production for loose and pelleted biomass under different pretreatment conditions and enzyme loadings with 2000 MT/d capacity.

Biomass Form	Pretreatment	Enzyme Loading	Annual Ethanol Production (MMgal/y)
Loose	PT1	H	39.60
	PT2	H	46.88
	PT3	H	46.44
Pellets	PT1	H	46.93
	PT2	M	48.44
		H	48.63
	PT3	L	46.69
		M	47.40
		H	47.40

3.1. Capital Cost: Higher Enzyme Loadings Lower the Capital Cost

The capital cost of producing ethanol for each studied case listed in Table 3 was determined. No appreciable difference in total capital cost between different pretreatment scenarios is observed (Figure 2). The difference in highest capital cost for loose biomass and lowest capital cost for pelleted biomass is less than 15%. Similarly, the difference in capital costs within loose biomass and within pelleted biomass were within the range of up to 7%. The boiler and turbogenerator section is the costliest installed equipment section, followed by the wastewater treatment and pretreatment section for all cases. These sections together contribute to more than 50% of the total installed equipment costs for all cases. Even though they are the costliest systems, they are vital for an energy self-sufficient biorefinery. Turbogenerator uses the biorefinery's byproducts to produce heat and electricity used throughout the plant. The excess electricity can be sold to the grid to generate extra revenue. Similarly, the wastewater section treats the waste and recycles the water required for the processes.

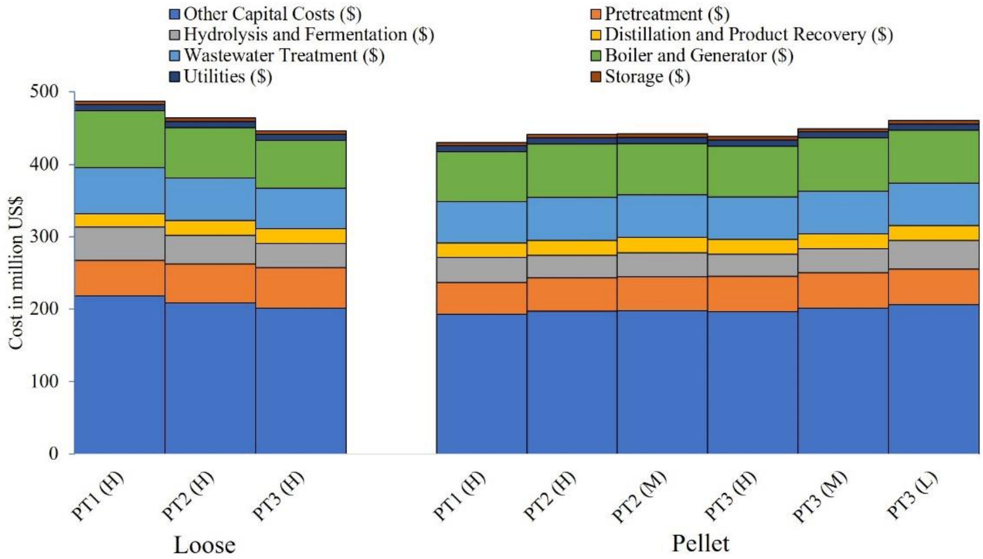

Figure 2. Capital cost breakdown into each area for loose and pelleted biomass under different pretreatment (PT1: 45 °C, 9 h, 12% ammonia; PT2: 50 °C, 14 h, 14% ammonia; PT3: 55 °C, 19 h, 16% ammonia) and enzyme loadings conditions (low, medium, and high enzyme loadings).

The capital cost trend in Figure 2 shows that with increasing pretreatment severity, the cost goes down for loose biomass as expected. Similarly, for pelleted biomass, the capital cost is lowest when the enzyme loadings are highest; however, the cost differences are not as apparent as they are with the loose biomass. Though the use of pelleted biomass allows doubling the pretreatment solid loadings, the cost advantage is small in the context of total equipment cost. Among the conditions for pelleted biomass, there is not a huge difference in capital costs between different processing conditions. PT3 at low enzyme loadings has the highest capital cost while PT1 at high enzyme loadings has the lowest. The pretreatment area's cost is lower as it requires a fewer number of reactors. This is because PT1 with high enzyme loadings has less pretreatment time, which means the process requires a fewer number of reactors for pretreatment. Moreover, hydrolysis cost is directly dependent on the selected pretreatment conditions and enzyme loadings. Higher severity pretreatment conditions with higher enzyme loadings lead to lower hydrolysis equipment cost. Although the pretreatment cost is lower at lower severity, the hydrolysis cost increases with lower severity pretreatment, reducing the combined cost for pretreatment and hydrolysis. Because of this, there was no appreciable difference in capital costs between different processing conditions. Other capital costs include warehouse and site development, construction, land, working capital, and other contingencies, which are a fixed percentage of direct costs. The difference in total capital investment for the best conditions for loose and pelleted biomass is just 4%.

The capital investment required for SAA pretreatment ranges from USD 9 to 12/gal ethanol produced, which is high compared to reports for other pretreatment methods like dilute acid, ammonia fiber expansion, and hot water [33]. The capital investment required for other pretreatment technologies varies between USD 3.05 and 5.55/gal ethanol produced (adjusted to 2017 USD) [26]. Although SAA pretreatment does not require high temperature and expensive pretreatment reactors, the cost–benefit in those areas is small compared to the additional cost of ammonia recovery that is required in the process.

3.2. Operating Cost: Lower Enzyme Loadings Lower the Operating Cost

The breakdown of annual operating costs (both fixed and variable) per gallon of ethanol for each form of biomass under different pretreatment conditions are shown in Figure 3. The trend shows that for loose biomass, the operating cost is higher with less severe pretreatments because of higher enzyme loadings and processing time requirements. However, the by-product credit is also higher at lower pretreatment severities which in turn partially offsets the higher operating costs of pretreatment for loose stover. Lower pretreatment severity conditions also require less steam. For pelleted biomass, the operating costs per gallon of ethanol are lower with lower enzyme loadings because enzymes are among the highest operating costs. Among all conditions modeled, PT3 at low enzyme loadings for pelleted biomass has the lowest operating cost, followed by PT2 at medium enzyme loadings.

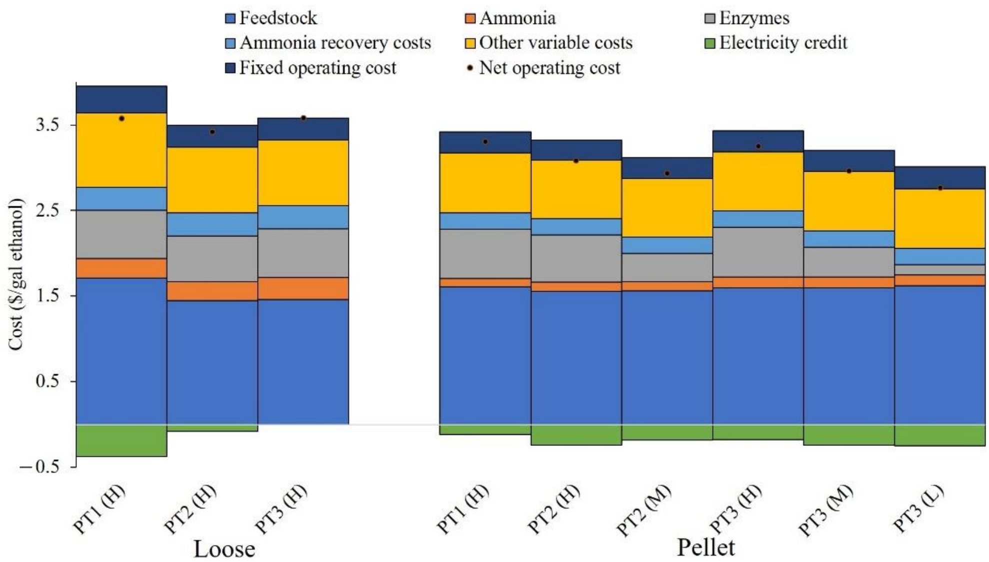

Figure 3. Breakdown of operating costs (variable and fixed) for loose and pelleted forms of biomass under different pretreatment conditions (PT1: 45 °C, 9 h, 12% ammonia; PT2: 50 °C, 14 h, 14% ammonia; PT3: 55 °C, 19 h, 16% ammonia) and enzyme loadings (high for loose biomass, and low, medium, high for pelleted biomass).

Among all operating variables, feedstock cost is the highest contributor to the final ethanol price and constitutes a bigger portion for pelleted than loose biomass. This is expected because of the additional cost required for pelleting, which is only partially offset by transportation and handling cost reductions. The ammonia cost contribution is twice as high for loose biomass (USD 0.22 to 0.26/gal) as it is for pelleted biomass (USD 0.10 to 0.13/gal). Loose biomass processing requires USD 0.27/gal ethanol for ammonia recovery while pelleted biomass requires only USD 0.19/gal ethanol produced (adjusted to varied ammonia loading and 2017 USD) [34]. The reason for lower ammonia-associated costs with pelleted biomass is because pellets can be processed with higher pretreatment solids loading. Enzyme use is another costly operating variable. Enzyme costs range between USD 0.54 and 0.57/gal for loose biomass and from USD 0.12 to 0.58/gal for pelleted biomass. Lower enzyme costs for pelleted biomass result from enzyme loading reductions by 80% [5] compared to loose biomass.

3.3. Minimum Ethanol Selling Price (MESP) under Different Scenarios

The minimum ethanol selling price (MESP) for both loose and pelleted biomass under different pretreatment conditions is shown in Table 6. MESP results show that the conditions resulting in the lowest operating cost also have the lowest MESP. Annualized capital and operating cost result show that operating cost has a higher contribution than the capital cost in MESP. MESP varies between USD 3.83 and 4.87/gal ethanol. The lowest cost was USD 3.83/gal for pelleted biomass at PT3 with low enzyme loadings. The highest cost for pellets was USD 4.29/gal at PT1 with high enzyme loadings, and this cost was still lower than the cost of producing ethanol with loose biomass under any scenario. The minimum cost for loose biomass was USD 4.41/gal ethanol with PT2 at high enzyme loading.

Table 6. Minimum ethanol selling price (MESP) for loose and pelleted biomass under different pretreatment conditions and enzyme loadings (PT1, PT2, PT3, and low, medium, high enzyme loadings).

Biomass Form	Pretreatment	Enzyme Loading	Minimum Ethanol Selling Price (MESP) (USD/gal)
Loose	PT1	H	4.87
	PT2	H	4.41
	PT3	H	4.54
Pellets	PT1	H	4.29
	PT2	M	3.91
		H	4.05
	PT3	L	3.83
		M	3.98
		H	4.24

3.4. Sensitivity Analysis: Process Conversion Rates Have a Higher Influence on MESP Compared to Market Condition and Process Time Duration

For sensitivity analysis, PT2 at high enzyme loadings with loose biomass, and PT3 at low enzyme loadings with pelleted biomass were chosen as base case scenarios because they resulted in the lowest ethanol selling prices. The lower and upper limits of input parameters tested (Table 7) are based on lab experiments and other research studies [13,26]. We determined the MSPs at both least favorable and favorable scenarios for each parameter. This will give a range in MSP for each parameter changes. Sensitivity analysis helps us to identify the hotspots in process economics, which can be further improved to get higher economic benefits.

Table 7. Sensitivity analysis assumptions for loose (PT2 at high enzyme loadings) and pelleted biomass (PT3 at low enzyme loadings).

Parameters	Scenarios		
	Least Favorable	Base Case	Favorable
Feedstock price (USD /MT)			
Loose biomass	110	95	80
Pelleted biomass	120	106	90
Enzyme protein cost (USD/kg)	8	6	4
Hydrolysis solids loading (g/L × 10)	5	10	20
Hydrolysis time (h)			
Loose biomass	48	33	24
Pelleted biomass	60	48	36
Fermentation time (h)	48	36	24
Ammonia loss (%)	3	2	1
Glucan to glucose (%)	75	90	95
Xylan to xylose (%)			
Loose biomass	50	72	90
Pelleted biomass	50	62	90
Glucose to ethanol (%)	85	95	98
Xylose to ethanol (%)	75	85	95
Fixed capital investment	+25%	-	−25%

The results of MESP sensitivity to variation in selected input parameters show that MESP is highly sensitive to changes in xylan conversion to xylose followed by hydrolysis solids loading and capital investment (Figure 4). We observed a lower value (62%) for xylose conversion based on our experimental results than is used elsewhere [13]. Increasing xylan conversion yield helps to increase ethanol yield and also concentration during distillation, thus reducing energy requirement for distillation. Increasing solids loading in hydrolysis reduces the required number of hydrolysis reactors along with the reduction in energy for distillation due to an increase in ethanol concentration. The enzyme use is not a significant factor for pelleted biomass because enzyme loading is reduced almost by 80% [5] under low enzyme loadings than under high enzyme loadings. Low enzyme loadings may have contributed to lower xylose yield. This can be overcome by additional xylanase supplementation during hydrolysis. Feedstock cost also has a high contribution to MESP. Feedstock cost includes transportation, handling, and storage. Developing a cost-effective supply system is crucial in the development of lignocellulosic biorefineries. Pelleting biomass can be one option to simplify logistics and reducing downstream processing costs. Interestingly, assumptions related to fermentation and hydrolysis time had little impact on MESP. Although longer hydrolysis and fermentation times increase capital costs, the cost increases have minimal impact on the overall MESP.

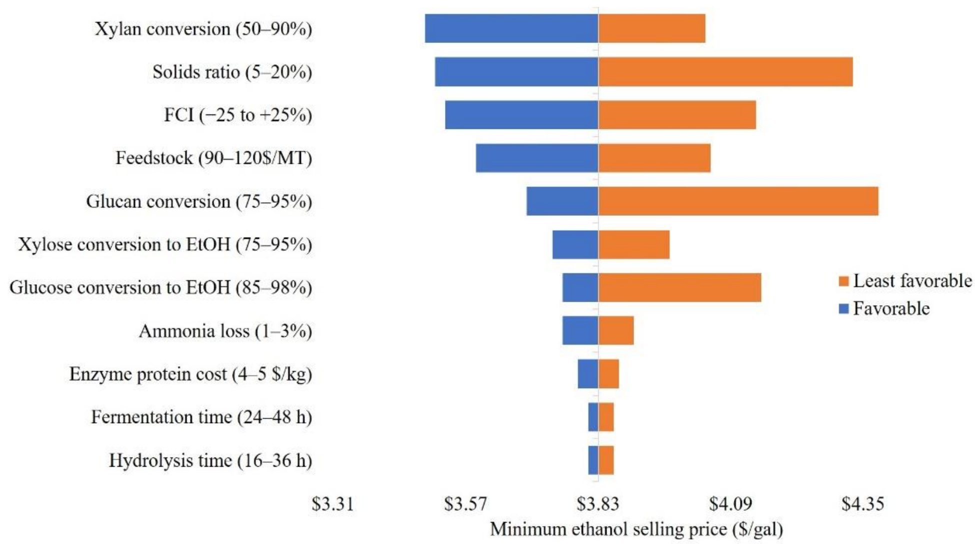

Figure 4. Sensitivity analysis for PT3 (55 °C 19 h, 16% ammonia) at low enzyme loadings for pelleted biomass.

For loose biomass (Figure 5), most of the parameters showed a similar sensitivity response to what was seen with the pelleted biomass. MESP is highly sensitive to changes in hydrolysis solids loading, xylan conversion to xylose, and capital investment. Xylan conversion is a bit higher (72%) compared to pelleted biomass. This might be due to higher enzyme loadings. Enzyme has a higher contribution in MESP for loose biomass compared to pelleted biomass. This is because the volume of the enzyme is 400% more for loose biomass.

Looking at both sensitivity analyses, the biggest opportunity to reduce final ethanol prices could come from focusing on the conversion of carbohydrates to sugars as well as increasing solids loading in hydrolysis. Use of pelleted biomass may offer a higher advantage in solids loading during hydrolysis because of the higher particle density of pellets compared to loose biomass. We did not conduct a laboratory study on the effects of varying solids loading during hydrolysis. In dilute acid pretreatment, parameters like capital cost, cellulose to glucose, xylose to ethanol were the most sensitive parameters [13]. In another similar study, ethanol price was found to be more sensitive to feedstock, enzyme, and installed equipment costs [35]. In a paper that studied the production of sugars from cellulosic biomass following ionic liquid pretreatment, the cost of the sugar obtained was highly sensitive to ionic liquid cost and its recovery process [36].

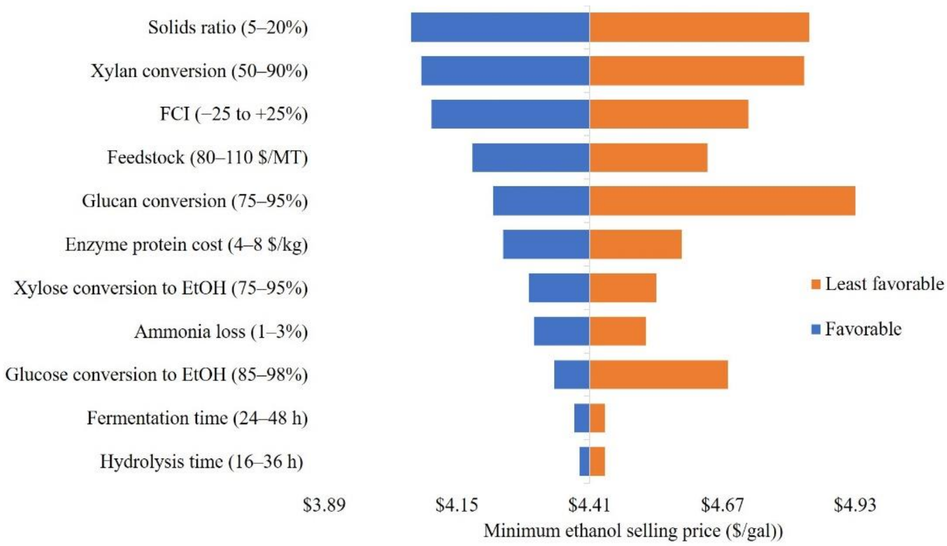

Figure 5. Sensitivity analysis for PT2 (PT2: 50 °C, 14 h, 14% ammonia) at high enzyme loadings for loose biomass.

3.5. Life Cycle Analysis: Downstream Processing Benefits Outweighs Higher Energy Use during Pelleting

The life cycle result showed that both loose and pelleted biomass systems did not meet the renewable fuel standard criteria to reduce 60% greenhouse gas emission compared to conventional fuel (Figure 6). However, pelleted biomass showed a promising future towards that direction. The results showed that pelleted biomass achieved a 48% reduction while loose biomass had a 5% higher emission compared to gasoline. Emission in kg CO_2 eq/MJ of fuel for pelleted biomass was 0.048 and from loose biomass was 0.097 compared to 0.093 from gasoline.

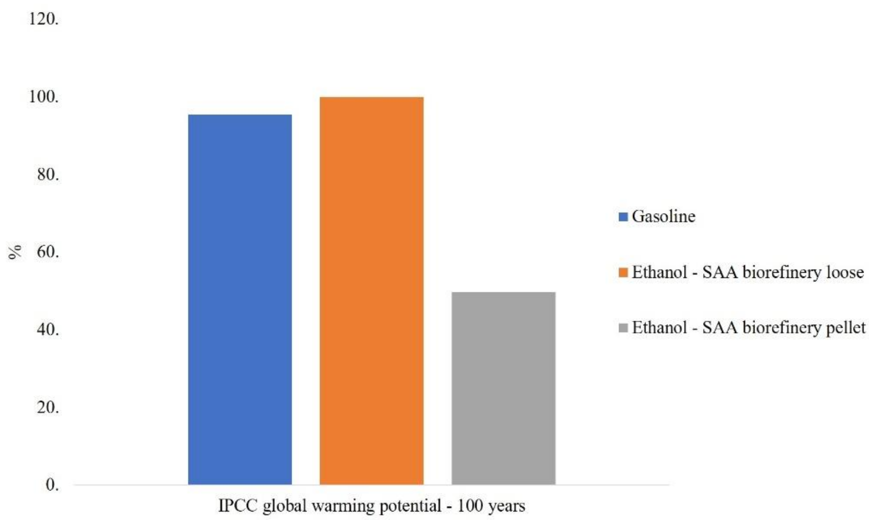

Figure 6. Comparison of the global warming impact of 1 Megajoule (MJ) gasoline, 1 MJ ethanol using loose and pelleted biomass.

For pelleted biomass, the major contribution to the total GHG emissions came from the biorefinery processing itself, followed by the pelleting process (Figure 7). The emission from biorefinery includes areas such as boiler and distillation process. The pelleting process also requires a high amount of energy. Biorefinery chemicals were not a big contributor for pelleted biomass processing. In contrast, the chemicals in the biorefinery for loose biomass were major contributor being responsible for almost 35 percent compared to just 6% for pelleted biomass. This came from the fact that processing loose biomass required higher ammonia and enzymes. Among chemicals, enzyme was the major GHGs emission contributor which is in agreement with the previous study [37]. Almost 90% of the emission originated from enzyme production in the chemicals part. Emission from boiler combustion accounts for 35% and 40% for loose and pelleted biomass, respectively.

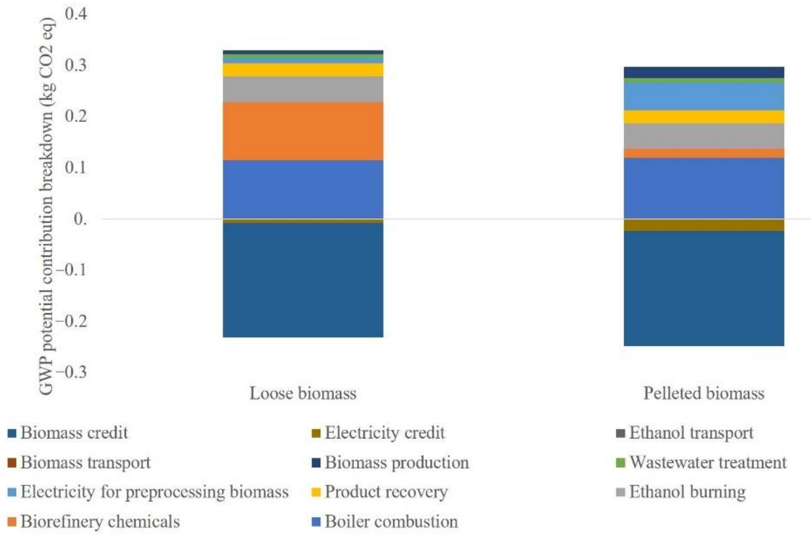

Figure 7. Emission breakdown for 1 MJ ethanol from loose and pelleted biomass.

Comparing between these two options we see that even though pelleting is an energy-intensive process, the added emission is offset by downstream processing benefits. There is also room for improvements in pelleting as emerging energy-efficient pelleting processes become available, which will have a positive impact on the overall production pathway. These results, however, are from a single study and there can be inherent uncertainties associated with it. Nevertheless, the overall trend from both economic and life cycle environmental analyses showed that pelleting biomass is beneficial in reducing pretreatment severities. In addition to soaking in aqueous ammonia, other biomass pretreatment systems need to be tested to better understand if pelleting biomass can lower their severity in terms of enzymes and chemicals requirement.

4. Conclusions

Using pelleted versus loose biomass as a biorefinery feedstock is a more economical option that can offer lower environmental impacts. Though pelleting is an additional step needed for pelleted biomass that also comes with additional cost and energy requirement, the downstream processing benefits outweighs such cost and emission burden from the pelleting process. The investigated MESP trend showed that lower operating costs and higher ethanol yield result in lower MESPs. All the scenarios analyzed for pelleted biomass resulted in lower MESPs than any conditions used for loose biomass. The lowest MESP for loose biomass and pelleted biomass was USD 4.41/gal ethanol and USD 3.83/gal ethanol, respectively. Life cycle assessment results showed that using pelleted biomass can reduce 50% of ethanol's GHG emissions compared to gasoline. In the presence of a carbon tax/credit policy, SAA ethanol that uses pelleted biomass will be competitive with gasoline in the market. New cost-effective and energy-efficient technologies are crucial for lowering the environmental impact and cost of pelleting. Use of pelleted biomass also offers more processing options than loose biomass, which can provide production flexibility depending on the enzyme and energy costs. Increasing the solids loading and xylan conversion during hydrolysis are the most important parameters to reduce ethanol price. The biorefinery processing benefits of using pelleted biomass should be tested for other types of biomass pretreatment including dilute acid at lower pretreatment severity and hydrolysis conditions compared to loose biomass.

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Appendix A

Table A1. Composition of untreated and pretreated loose and pelleted corn stover (adapted from [5]).

Treatments	Solids Recovered (%)	Glucan (%)	Xylan (%)	Total Lignin (%)
		Loose Corn Stover		
UT	-	31.2 ± 1.0	20.8 ± 1.8	18.9 ± 0.4
PT1	74.2	35.1 ± 0.1	21.9 ± 0.1	15.3 ± 0.7
PT2	71.7	40.9 ± 1.8	26.5 ± 0.7	12.4 ± 0.2
PT3	70.5	44.1 ± 2.9	27.5 ± 4.4	10.8 ± 0.1
		Pelleted Corn Stover		
UT	-	32.0 ± 1.6	21.0 ± 1.1	17.3 ± 0.2
PT1	77.3	40.6 ± 0.2	25.0 ± 0.3	12.7 ± 0.9
PT2	72.3	43.3 ± 1.4	24.8 ± 0.9	11.9 ± 1.1
PT3	68.6	47.2 ± 0.7	24.3 ± 0.3	9.6 ± 0.1

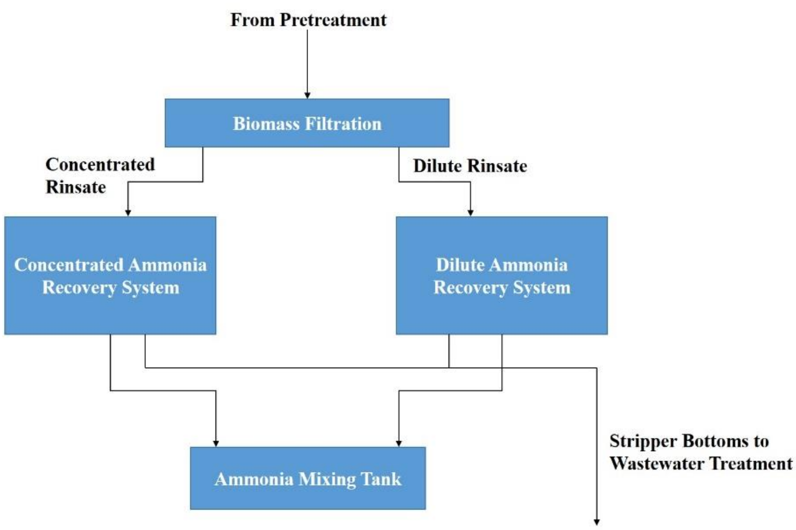

Figure A1. Details on ammonia recovery system.

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