Applied Energy 242 (2019) 1467–1496

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Moving second generation biofuel manufacturing forward: Investigating economic viability and environmental sustainability considering two strategies for supply chain restructuring

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HIGHLIGHTS

- Substitution of 2nd generation for 1st generation biofuel is investigated.
- An optimization model for the 2nd generation biofuel supply chain is proposed.
- Both economic and environmental performance measures are examined.
- 2nd generation biofuel is more cost effective than 1st generation biofuel.
- Considering stover handling or not leads to different environmental performances.

ARTICLE INFO

Keywords:
Biofuel supply chain
Biomass preprocessing
Greenhouse gas emission
Cellulosic biofuel manufacturing
Corn stover

ABSTRACT

Multiple generations of biofuel manufacturing technologies have been proposed and developed, among which first generation technology is the most mature. It typically utilizes corn grain as feedstock in bio-refineries in many countries such as the United States. However, the use of edible matter of crops like corn may lead to a food-versus-fuel competition. To address such an issue, second generation biofuel manufacturing technology using the non-edible matter of crops has been developed. In this paper, the economic viability and environmental sustainability are analyzed and quantified, when restructuring the biofuel supply chain from employing first generation manufacturing technology to the one utilizing second generation technology considering the existing supply chain infrastructure. Two supply chain restructuring strategies, i.e., distributed and centralized preprocessing deployment, are modeled for implementing biomass preprocessing for second generation biofuel manufacturing. Bi-objective optimization formulations for the corn stover-sourced biofuel (a typical second generation biofuel) supply chain considering both economic and environmental aspects are proposed under both strategies. Different decision variables such as the locations selected for constructing preprocessing centers and the corresponding corn stover handling capacities of such centers, as well as the material flows between farms, preprocessing centers, and bio-refinery plants are identified. A case study based on the state of Missouri in the United States is implemented to illustrate the effectiveness of the proposed model and analyze the performance of different strategies. The results of the case study show that when corn stover is used as feedstock in bio-refineries, the unit cost of bioethanol production can be reduced, while the unit emission is increased compared to the corn-sourced supply chain under both supply chain restructuring strategies. Specifically, in Missouri where the daily stover handling amount per bio-refinery plant is relatively low and the stover collection radius is relatively small, the centralized strategy outperforms the distributed one with a higher cost reduction and a smaller increase in emissions. It reduces the unit cost by 27.39%, while increasing the unit emission by 24.42%, compared to the corn-sourced supply chain.

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https://doi.org/10.1016/j.apenergy.2019.03.098
Received 26 October 2018; Received in revised form 22 February 2019; Accepted 8 March 2019
Available online 27 March 2019

1. Introduction

Biofuel is considered a promising alternative to traditional fossil fuels. In the past several decades, biofuel manufacturing technologies have witnessed a rapid advancement and four generations of biofuels have been developed or proposed [1]. First generation biofuel refers to the fuels that are derived from sources like starch, sugar, animal fats, and vegetable oil. Second generation biofuel is produced by cellulosic biomass, mainly from non-edible matter of crops [1]. Third generation biofuel refers to the biofuel produced from algae [2]. Fourth generation biofuel aims to capture and store CO_2 at all stages of production [3].

The production technology for first generation biofuel is the most mature. The most popular biomass types used in first generation biofuel production mainly include corn and sugarcane, which are widely used in the United States and Brazil, respectively [4]. Specifically, bioethanol is produced in bio-refinery plants using the feedstock of corn grain purchased from nearby farms. A hammer milling system is typically employed in these bio-refinery plants to process the corn so that it can be used in the hydrolysis and fermentation to produce bioethanol.

A corn-sourced biofuel supply chain network is beneficial because the regions with large amounts of corn production, such as the states located in the corn-belt region in the United States [5], can direct the surplus corn output towards bioethanol production. However, since corn has been traditionally used as one of the primary food grains for humans and animals [6], the use of corn for energy production causes food-versus-fuel competition. This may lead to a shortage of food, particularly for those who cannot afford high food prices.

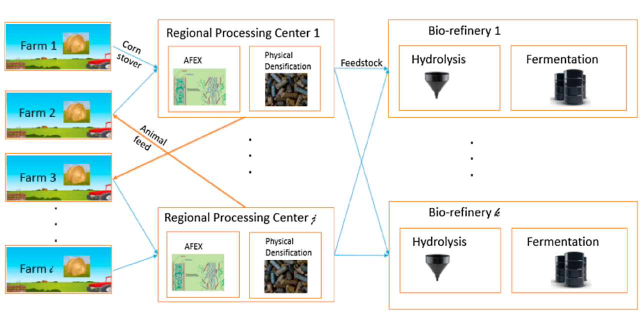
To address such a major limitation of first generation biofuel, second generation biofuel, or cellulosic-based biofuel, has been proposed. It mainly utilizes non-edible matter from crops, such as corn stover, big bluestem, sorghum stalk, and wheat straw. At present, the cellulosic-bioethanol industry is still in its infancy due to predominant usage of corn grain in bioethanol production in the United States. The country has set a plan of producing up to 16 billion gallons of second generation biofuel by 2022 [7]. Therefore, research focusing on the second generation biofuel production has been widely conducted [8–10]. This technology is particularly attractive because (1) the biomass cost in the supply chain can be reduced since the price of non-edible crop matter like corn stover is much lower than corn grain [11,12], (2) the price escalation of corn can be controlled as it will not lead to a food-versus-fuel competition, and (3) a secondary product of the pretreated biomass can be largely sold back to the farms as animal feed in the areas, especially where animal farm and corn farm are typically run by the same owner if specific pretreatment methods are used. Thus, in turn, the price stability and business relationship between the farms and bio-refinery plants can be improved and maintained. [13].

Cellulosic biomass typically consists of various chemical compositions such as lignin, hemicellulose, and cellulose. These compositions have a lower energy density compared to the biomass of corn grains. Essentially, to facilitate the production of second generation biofuel, chemical pretreatment to break the lignin seal around the cellulose is needed, and physical densification to densify the biomass may also be required to increase the energy density of the cellulosic biomass feedstock [14–16]. Therefore, additional facility handling is required for preprocessing activities including both chemical pretreatment and physical densification. This is needed so that the qualified feedstock of preprocessed non-edible crop matter can be provided in the hydrolysis and fermentation in bio-refinery plants to produce second generation biofuel.

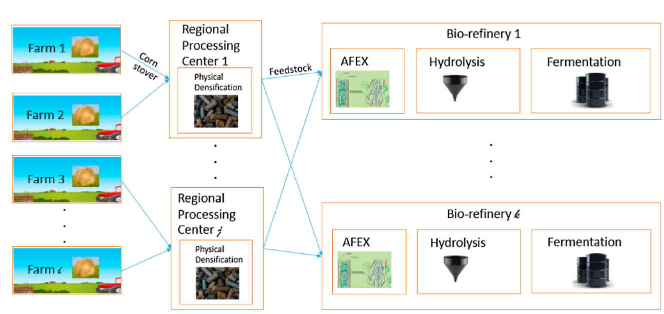
Various studies of different methods for physical densification and chemical pretreatment in preprocessing have been reported in literature. The physical densification typically employs milling, grinding, chopping, and pelleting to reduce the size and increase the density of the cellulosic biomass. For example, pelleting technologies have been widely studied to reduce the particle size of biomass for non-edible crop matter [17,18]. The effects of the pelleting parameters on the processing characteristics of wheat straw [19], corn stover, and sorghum stalk [20,21] have been investigated. A production scheduling model for cellulosic biomass grinding considering work-in-process particle separation was proposed to reduce energy waste and improve energy efficiency when densifying the biomass [22].

Chemical pretreatment technologies involve options such as dilute acid and sulfur dioxide pretreatment, controlled pH pretreatment, ammonia fiber expansion (AFEX) pretreatment, and lime pretreatment to break the lignin structure in cellulosic biomass for increasing enzyme accessibility to cellulose, thus improving the sugar yield post fermentation [15,16]. For example, the AFEX consists of mixing the biomass in aqueous ammonia solution, increasing the pressure of the mixture, and then explosively releasing the pressure, causing breakage of the lignin bonds, pre-hydrolyzing of the hemicellulose, and de-polymerization of the cellulose content. This causes better enzyme accessibility during hydrolysis and fermentation, which results in an increased ethanol yield. More than 90% conversion of cellulose and hemicellulose to fermentable sugars can be achieved for various feedstocks even with low enzyme loadings (e.g., corn stover) [16]. In addition, corn stover treated by AFEX can be sold back to farms as animal feed with equivalent nutritional content to traditional animal feeds such as corn, sorghum, and beet pulp [13]. Compared to other pretreatment methods, AFEX pretreatment is a relatively dry process because of an almost complete recovery of ammonia (approximately 97%) [13,15,16]. Therefore, the AFEX treated biomass can be physically densified using the same method as the one used for raw biomass so that the AFEX pellets can have high energy density, low transportation cost, and high ethanol yield [14].

The facility for conducting biomass preprocessing can be deployed considering two different strategies (i.e., centralized and distributed) [23,24]. Centralized deployment was originally proposed, which intended to integrate the preprocessing of chemical pretreatment into the existing bio-refinery plant before hydrolysis, while the physical densification to reduce the size of biomass feedstock is not considered. Distributed preprocessing deployment was proposed later. It can be carried



a. Pathway 1



b. Pathway 2

Fig. 1. Cellulosic biofuel supply chain with decentralized preprocessing deployment strategy.

out by two pathways: (1) Preprocessing activities including both chemical pretreatment and physical densification are conducted in preprocessing centers (also called quality depots [25]) (see Fig. 1a); (2) Physical densification is carried out in preprocessing centers (also called conventional depots [25]), and the physically densified biomass is transported to bio-refinery plants for further chemical preprocessing followed by hydrolysis and fermentation [23,24] (see Fig. 1b).

Many works in the literature compare the centralized and distributed deployment strategies [7,25]. For example, Kim et al. have discussed the effects of the size of a bio-refinery plant on the minimum ethanol selling price (MESP) considering the two deployment strategies, and have combined the economic and environmental objectives through an eco-efficiency indicator [7]. Later, the team proposed a supply chain model assuming the preprocessing centers are located at grain elevators and the bio-refinery plants are at the coal power plants, discussing the breakup of economic and environmental effects for both deployment strategies [25].

Generally, it has been recognized that the centralized deployment strategy is suitable for a supply chain with a relatively lower biomass handling capacity in a local area, i.e., no more than 5000 tons of biomass handled per day in a bio-refinery plant with a collection distance of 50–100 miles [23]. When the processing capacity is more than 5000 tons per day and the collection distance is about 100–300 miles, a centralized strategy may lead to a significant increase in transportation cost and logistic complexity since the density of cellulosic feedstocks is typically low without physical densification and the biomass has to be sourced from farms far away from the bio-refinery plant [7]. Thus, the distributed deployment strategy is considered superior to the centralized one in a cellulosic supply chain, when the overall production amount is large [23,24].

Despite a significant body of literature dedicated to supply chain modeling and techno-economic analysis for second generation biofuel manufacturing (see a brief literature review in Section 2), there is no study quantifying and analyzing the environmental and economic impacts when switching first generation bioethanol manufacturing using starchy feedstock to second generation bioethanol manufacturing using cellulosic feedstock considering the existing supply chain infrastructure. Many studies have focused on the techno-economic analysis for either various individual manufacturing processes or multiple manufacturing processes in the supply chain. The methods of laboratory experiments, process modeling, software simulation such as Aspen Plus [26], and commercial databases such as ICARUS [27] have been widely used, while the integration of an analytical optimization model seeking optimal performance for techno-economic analysis has been reported less. Meanwhile, the environmental performance has been modeled less often compared to economic concerns. For example, the transportation mode may be switched from a nonstop transportation between farms and bio-refinery plants in a corn-sourced supply chain to a one-stop mode with an intermediate stop for the proposed preprocessing centers in a distributed corn stover based supply chain. The variations of the transportation emissions and costs need to be examined.

In this work, we propose a biofuel supply chain model using second generation biofuel manufacturing technology considering the existing bio-refinery infrastructure and farms to examine the environmental and economic impacts when switching the biofuel manufacturing technology from first to second generation. Both distributed and centralized supply chain restructuring strategies are considered. AFEX is used as the chemical pretreatment method due to the aforementioned advantages of AFEX.

Some of the literature has investigated the order of physical densification and chemical pretreatment for the pathway 1 distributed preprocessing strategy. Although smaller biomass particle size can increase the effectiveness of AFEX by improving the glucan yield during hydrolysis [28,29], such benefits can only be realized in certain hydrolysis conditions [29] and there are no clear energy savings. On the other hand, if AFEX is performed before densification, the lignin content in the biomass is brought to the surface in the AFEX, and the lignin can then act like a natural binder for the formation of pellets during densification [30], resulting in more stable pellets for future transportation and storage at no additional cost for external binders. Further, it is also mentioned in the literature that pelleting the biomass after AFEX will increase the yield by around 10% compared to AFEX-treated biomass that is not pelletized [31]. Thus, when modeling the distributed supply chain of pathway 1 in this paper, we follow the order of chemical pretreatment through AFEX followed by physical densification as shown in Fig. 1a.

The goal of this paper is to explore the economic viability and environmental impact of using corn stover to replace corn grains in producing bioethanol following two supply chain restructuring strategies. The total cost and emission for each of the two strategies are formulated, optimized, and compared to the cost and emission of the bioethanol produced using first generation manufacturing technology. The models identify the location and capacity of the preprocessing center (for the distributed strategy), along with the transportation quantities between nodes in the supply chain. A case study using existing farms, bio-refinery plants, and fuel demand in the state of Missouri in the United States is implemented. The remainder of the paper is organized as follows: Section 2 gives a brief literature review in terms of techno-economic analysis and biofuel supply chain modeling for second generation biofuel manufacturing. Section 3 introduces the modeling methods for both corn-sourced and corn stover-sourced supply chain networks. Section 4 introduces a case study using relevant data from Missouri in the United States. Section 5 demonstrates the results of the case study along with sensitivity and stochastic analysis. Section 6 discusses the implications and limitations of this paper. Finally, conclusions are drawn and future work is proposed in Section 7.

2. Literature review

In this section, we briefly review the literature with respect to techno-economic analysis and supply chain modeling for second generation biofuel manufacturing. Many existing studies using techno-economic analysis have been reported. These studies have focused on cost effectiveness analysis, yield estimation, and energy consumption modeling for various individual processes ranging from biomass harvesting to biofuel bioconversion.

For harvesting, agriculture researchers have published many results following American Society of Agricultural and Biological Engineers (ASABE) platform. For example, Shinners et al. have performed an engineering efficiency analysis using different ASABE standards in their experiments for comparing the performance of three harvesting configurations in the single pass harvest of corn and corn stover [32,33]. Sokhansanj et al. have performed a cost analysis to find variations in the delivery cost of corn stover from harvesting to storage facilities at an intermediate distance from the farms due to the effects of corn stover yield and bale density [34].

For biomass size reduction, Sokhansanj and Turhollow have performed an engineering and economic analysis of the cubing and baling operations involved in the densification of corn stover [35]. Bitra et al. have performed an energy analysis on milling for three biomass feedstocks and have listed the effects of the feedstock particle sizes on the energy consumption [36]. Sokhansanj et al. have performed a techno-economic analysis of offering size-reduced and densified corn stover for providing heat and electricity to a corn ethanol plant [37].

For pelleting, Mani et al. have performed an economic analysis of various costs and plant capacities in the production of wood pellets from saw dust [38] and an energy analysis to find the effect of moisture content and compaction pressure in the production of corn stover pellets [39].

For pretreatment, Eggeman and Elander have conducted an economic analysis for five pretreatment processes in the production of bioethanol using corn stover [40]. Schell et al. have performed an analysis on the effect of two leading pretreatment options for two biomass feedstocks to find the ideal combination for yield and cost of bioethanol production [41]. Aden et al. have conducted a techno-economic analysis for determining the engineering solutions and their cost potential in simultaneous dilute acid pretreatment and enzymatic hydrolysis of corn stover [42].

For hydrolysis, Gregg et al. have used an engineering and economic model to evaluate the combined effects of enzyme recycling and hydrolysis time on the cost of bioethanol produced from wood [43]. Wingren et al. have evaluated and compared "separate hydrolysis and fermentation" and "simultaneous saccharification and fermentation" in the production of bioethanol from softwood by studying the effects of the enzyme loading and secondary income through coproducts [44].

For fermentation, Nguyen and Saddler have established a techno-economic simulation model for the hydrolysis and fermentation in cellulosic ethanol production and studied the effects of the interaction of the various process parameters on production cost [45]. Hinman et al. have performed a detailed engineering and cost analysis for the production of bioethanol through simultaneous saccharification and fermentation of wood chips and studied the effects of the plant capacity, enzyme loading, and raw material cost on the production cost of bioethanol [46].

For gasification, the discounted cash flow rate of return (DCFROR) method has been used by many researchers for investigating the cost of conversion of biomass to liquid fuels. For example, Swanson et al. have used this method to analyze the capital and production costs of converting biomass to biofuel through gasification [47]. Anex et al. have performed an analysis of capital and operating costs of six configurations based on the pyrolysis, gasification, and biochemical conversion of biomass to liquid fuels [48].

In addition, researchers from National Renewable Energy Laboratory, Idaho National Laboratory, and Oak Ridge National Laboratory have also reported a considerable body of literature covering multiple manufacturing processes for second generation biofuel, either physical processes to prepare feedstock or chemical processes for bioconversion.

For the feedstock preparation, Hess et al. have conducted a cost analysis of ethanol production to analyze the role and importance of feedstock availability and the various processes involved in feedstock handling [49]. Perlack and Turhollow have performed an analysis of the effect of bio-refinery capacity and feedstock availability on the collection, storage and hauling costs of corn stover for bioethanol production [50,51]. Turhollow et al. have performed a cost analysis of the labor, equipment, and material requirements in the preparation of feedstocks from agricultural crops and residues for biofuel production [52]. Jacobson et al. have reported an analysis for identifying the economically sustainable feedstocks as per the bio-refinery capacity for various regions of the United States [53].

For the processes relevant to bioconversion, McAloon et al. have compared various elements of the production costs of corn-ethanol and cellulosic-ethanol [54]. Cardona and Sanchez have conducted an energy analysis for calculating the net energy value of cellulosic bioethanol and compared it with ethanol derived from starch [55]. Kazi et al. have performed an engineering and cost analysis using DCFROR to compare various available pathways in pretreatment and bioconversion for commercialization of cellulosic ethanol [26].

As for the supply chain modeling, many works focusing on the performance evaluation of cellulosic biofuel supply chain have been reported in the literature. For example, Luo et al. have made an energy consumption analysis for the supply chain of bioethanol produced from corn stover [56]. Yue et al. have illustrated the economic and environmental performance of a biofuel supply chain through a functional-unit based life cycle optimization framework [57]. Balaman et al., have enabled a two stage design for the transportation network of a bio-product supply chain, through the usage of a fuzzy ϵ-constraint method [58].

Meanwhile, the feasibility of deploying preprocessing centers has also been reported. For example, Ng et al. have developed a few studies for the location, capacity, and inventory planning of the biofuel supply chain including preprocessing centers [59–61]. Carolan et al. have investigated the technical and financial feasibility of deploying regional preprocessing centers for implementing AFEX [13]. Kesharwani et al. have investigated the environmental feasibility of the inclusion of the densification operation into a cellulosic biofuel supply chain [62].

In summary, compared to the existing literature, the proposed model in this paper has the advantages that (1) it considers the existing infrastructure in biofuel supply chain when investigating both economic and environmental impacts for the switch from first generation biofuel to second generation biofuel manufacturing; (2) different supply chain restructuring strategies are modeled and examined for offering a systematic comparison for the decision maker; and (3) the results are based on an analytical optimization model to provide an achievable best performance of the supply chain using different strategies.

3. Method

In this section, the methods to estimate the cost and emissions for the corn-sourced and corn stover-sourced biofuel supply chains are introduced. The notation used is provided in Tables 1–3.

3.1. Corn-sourced biofuel supply chain

In this section, we establish the model to estimate the cost and emission per gallon of bioethanol produced in bio-refineries in corn-sourced biofuel supply chain. Let PP_k^c be the cost per gallon of bioethanol produced at bio-refinery plant k. It is calculated through dividing the total cost for producing bioethanol at bio-refinery plant k by the total bioethanol in gallons that can be produced using corn in bio-refinery plant k. The total cost for producing bioethanol at bio-refinery plant k includes the material purchase cost, the transportation cost, the raw material (corn) holding cost, and the operation costs of milling, hydrolysis and fermentation.

Let PE^c be the emission per gallon of bioethanol produced in the supply chain when corn grain is used as feedstock. It is calculated through dividing the total emission incurred by producing bioethanol using corn in the supply chain by the total bioethanol in gallons that can be produced in the supply chain. The total emissions include the

Table 1
List of indexes.

Index	Description
i	Index of farms
j	Index of candidate preprocessing centers
k	Index of bio-refinery plants

Table 2
List of variables.

Variable	Description
Binary decision variables	
x_j	Binary decision variable to denote if candidate preprocessing center j is selected or not, one if selected, zero otherwise
y_j	Corn stover handling capacity (tons/year) of preprocessing center j
Continuos nonnegative decision variables	
$b_{f_i p_j}$	Tons of corn stover transported from farm i to preprocessing center j
$b_{f_i b_k}$	Tons of corn stover transported from farm i to bio-refinery plant k
$b_{p_j b_k}$	Tons of preprocessed corn stover transported from preprocessing center j to bio-refinery plant k

Table 3
List of parameters.

Parameter	Description
Cost related parameters	
$1/d$	Fraction of yearly biomass demand for production specified as the inventory level of the raw materials at bio-refinery plants
a^{sC}	Cost per unit yearly capacity ($/ton) for building a chemical pretreatment system
b^{sC}	Fixed cost ($) for building a chemical pretreatment system
F_j	Selling price ($/ton) of animal feed obtained from the secondary products of chemically pretreated biomass in preprocessing center *j* in the distributed supply chain built by pathway 1
G_P	Investment ($) of a single system for physical densification in the preprocessing center
o^{cF}	Operating cost ($/ton) of hydrolyzed corn mash in fermentation at bio-refinery plants
o^{cH}	Operating cost ($/ton) of milled corn mash in hydrolysis at bio-refinery plants
o^{cM}	Operating cost ($/ton) of milling at bio-refinery plants
o^{sC}	Operating cost ($/ton) of corn stover processed in chemical pretreatment
o^{sF}	Operating cost ($/ton) of hydrolyzed corn stover slurry in fermentation
o^{sH}	Operating cost ($/ton) of preprocessed corn stover slurry in hydrolysis
o^{sP}	Operating cost ($/ton) of corn stover processed in physical densification
P_i^c	Selling price ($/ton) of the corn sold by farm *i* to bio-refinery plants
P_i^s	Selling price ($/ton) of the corn stover sold by farm *i* to preprocessing centers
$T^{su}_{f_i p_j}$	Cost ($/truck/mile) of corn stover transported from farm *i* to preprocessing center *j*
$T^{sp}_{p_j b_k}$	Cost ($/truck/mile) of preprocessed corn stover transported from preprocessing center *j* to bio-refinery plant *k*
$T^{c}_{f_i b_k}$	Cost ($/truck/mile) of corn transported from farm *i* to bio-refinery plant *k*
z_j	Selling price ($/ton) of preprocessed corn stover at preprocessing center *j*
Emission related parameters	
α	Rate of GHG emission increase (lbs. of CO_2/mile) when unit load is added to a truck in transportation
e^0	GHG emission (lbs. of CO_2/mile) of transportation truck per unit distance without load
e^{cF}	GHG emission (lbs. of CO_2/ton) of hydrolyzed corn mash in fermentation
e^{cH}	GHG emission (lbs. of CO_2/ton) of milled corn mash (mixture of milled corn and water) in hydrolysis
e^{cM}	GHG emission (lbs. of CO_2/ton) of corn grain in milling
e^{sC}	GHG emission (lbs. of CO_2/ton) of corn stover processed in chemical pretreatment
e^{sF}	GHG emission (lbs. of CO_2/ton) of hydrolyzed corn stover slurry in fermentation
e^{sH}	GHG emission (lbs. of CO_2/ton) of preprocessed corn stover slurry (mixture of preprocessed corn stover and water) in hydrolysis
e^{sP}	GHG emission (lbs. of CO_2/ton) of corn stover processed in physical densification
Transportation related parameters	
B_{ik}	Amount of corn (tons) transported from farm *i* to bio-refinery plant *k*
$D_{f_i p_j}$	Distance (miles) from farm *i* to preprocessing center *j*
$D_{p_j b_k}$	Distance (miles) from preprocessing center *j* to bio-refinery plant *k*
$D_{f_i b_k}$	Distance (miles) from farm *i* to bio-refinery plant *k*
Capacity related parameters	
δ_j^s	Percentage of the post chemical pretreated corn stover from preprocessing center *j* that is sold back to the farms as the animal feed in the distributed supply chain built by pathway 1
g_p	Yearly capacity of a physical densification system in preprocessing centers
K	Maximum corn stover intake capacity (tons/year) for preprocessing centers
M^c	Maximum mass of corn grain (tons) that can be transported by a truck
M^{sp}	Maximum mass of densified corn stover (tons) that can be transported by a truck
M^{su}	Maximum mass of corn stover (tons) that can be transported by a truck
Q_i	Capacity (tons) of corn stover that can be supplied by farm *i*
W_k^s	Preprocessed (chemically and physically) corn stover handling capacity (tons) at bio-refinery plant *k*
Process related parameters	
β^{cH}	Mass transition factor from corn mash to hydrolyzed corn slurry in bio-refinery plants
β^{cM}	Mass transition factor from corn to corn mash in bio-refinery plants
β^{sC}	Mass transition factor from corn stover to chemically pretreated corn stover in the preprocessing centers
β^{sH}	Mass transition factor from pre-hydrolyzed corn stover slurry to hydrolyzed corn stover slurry
β^{sL}	Mass transition factor from preprocessed corn stover to pre-hydrolyzed corn stover slurry
β^{sP}	Mass transition factor in physical densification in the preprocessing center in the distributed supply chain
σ_k^c	Bioethanol conversion coefficient (gallons per ton of milled corn) at bio-refinery plant *k* when corn is used as feedstock
σ_k^s	Bioethanol conversion coefficient (gallons per ton of preprocessed corn stover) at bio-refinery plant *k* when preprocessed corn stover is used as feedstock
Miscellaneous parameters	
N	A large real number
r	Annual discount rate
T	Lifetime (years) of the preprocessing center

Table 4
Farm location, annual yield, and selling price (corn and corn stover) in Missouri.

County code #	County	Latitude	Longitude	Mean of corn/corn stover supply capacity (ton)	County code #	County	Latitude	Longitude	Mean of corn/corn stover supply capacity (ton)
1	Andrew	39.96	−94.81	150,397	33	Laclede	37.7	−92.54	5213
2	Atchison	40.42	−95.48	385,424	34	Maries	38.17	−91.95	4055
3	Caldwell	39.67	−93.99	49,548	35	Miller	38.21	−92.38	3475
4	Clay	39.32	−94.48	37,325	36	Morgan	38.37	−92.86	13,244
5	Clinton	39.65	−94.48	123,678	37	Osage	38.39	−91.91	28,927
6	Daviess	40	−93.99	103,530	38	Pettis	38.69	−93.34	163,747
7	Holt	40.07	−95.19	315,805	39	Polk	37.68	−93.34	5882
8	Nodaway	40.29	−94.81	379,055	40	Saline	39.19	−93.18	447,882
9	Ray	39.34	−93.99	119,855	41	Franklin	38.4	−91.14	52,733
10	Worth	40.47	−94.32	40,632	42	Gasconade	38.43	−91.48	15,819
11	Adair	40.2	−92.54	46,500	43	Jefferson	38.23	−90.53	5412
12	Chariton	39.53	−93.02	227,774	44	Perry	37.72	−89.78	76,066
13	Randolph	39.42	−92.5	45,858	45	St Charles	38.73	−90.83	120,510
14	Sullivan	40.18	−93.18	44,137	46	Ste Genevieve	37.89	−90.22	39,397
15	Audrain	39.22	−91.91	278,525	47	St Francois	37.77	−90.49	3764
16	Knox	40.21	−92.22	157,408	48	St Louis	38.61	−90.41	10,638
17	Lewis	40.05	−91.75	178,195	49	Warren	38.73	−91.14	50,598
18	Marion	39.85	−91.64	168,639	50	Barry	36.64	−93.83	15,531
19	Monroe	39.55	−92.07	168,593	51	Barton	37.48	−94.32	170,393
20	Pike	39.4	−91.29	186,120	52	Christian	37	−93.18	2956
21	Scotland	40.49	−92.18	126,194	53	Dade	37.49	−93.99	41,303
22	Shelby	39.84	−92.11	155,882	54	Greene	37.33	−93.5	4648
23	Cass	38.66	−94.32	83,520	55	Lawrence	37.15	−93.83	25,117
24	Henry	38.34	−93.83	46,195	56	Howell	36.85	−91.91	2866
25	Johnson	38.67	−93.83	114,185	57	Webster	37.35	−92.86	4283
26	Lafayette	39	−93.99	323,181	58	Butler	36.7	−90.38	69,833
27	St Clair	38	−93.83	35,511	59	Cape Girardeau	37.38	−89.63	83,322
28	Boone	39.05	−92.38	64,117	60	Mississippi	36.87	−89.32	199,075
29	Callaway	38.89	−91.91	88,578	61	New Madrid	36.52	−89.78	206,268
30	Cole	38.51	−92.26	12,771	62	Pemiscot	36.22	−89.81	66,923
31	Dallas	37.69	−93.02	1327	63	Stoddard	36.87	−89.93	233,093
32	Hickory	37.98	−93.3	6630					

transportation emissions when transporting corn grains from various farms to bio-refinery plants and processing emissions incurred in milling, hydrolysis, and fermentation at bio-refinery plants. Note that, the scope of this research is from the purchase and transportation of the biomass from the farms. The emissions incurred in earlier stages like harvesting are not included. While, the possible influences on the model results due to not considering the harvesting system are discussed in Section 6. The details of the calculation can be found in Appendix A.

3.2. Corn stover-sourced biofuel supply chain using distributed preprocessing strategy

In this section, a corn stover-sourced biofuel supply chain model with two pathways for distributed preprocessing center deployment is introduced.

3.2.1. Pathway 1: Chemical pretreatment and physical densification in preprocessing center

In this section, the corn stover-sourced distributed biofuel supply chain model considering pathway 1 is formulated (for simplicity, this model is referred to as pathway 1 supply chain in the remainder of the paper). In the model, both chemical pretreatment and physical densification are conducted in the proposed preprocessing facility. The objective is to identify the locations for building the preprocessing centers, the capacities of the preprocessing centers, and the material flows, that minimize the emissions and cost of bioethanol produced under the various constraints (e.g., bioethanol demand needs to be met). The objective function is formulated by (1) through a conventional weighted sum method with two weights w_1 and w_2 between zero and one assigned to two objectives. Note that the superscript "$sd1$" is used to denote the notations used in the pathway 1 supply chain.

$$\min_{x_j^{sd1}, y_j^{sd1}, b_{f_i p_j}^{sd1}, b_{p_j b_k}^{sd1}} w_1 E^{sd1} + w_2 C^{sd1} \tag{1}$$

In (1), E^{sd1} is the total emissions from biofuel manufacturing when corn stover is used as the feedstock. It consists of the emissions from the transportation of corn stover from farms to preprocessing centers, the emissions due to the preprocessing activities of chemical pretreatment and densification at preprocessing centers, the emissions from transportation of preprocessed corn stover from preprocessing centers to bio-refinery plants, and the emission due to the bioconversion activities of hydrolysis and fermentation at bio-refinery plants. E^{sd1} can be calculated by (2).

$$\begin{aligned} E^{sd1} &= \textstyle\sum_i \sum_j \left[(e^0 + \alpha M^{su}) \cdot D_{f_i p_j} + e^0 D_{f_i p_j}\right] \left\lceil b_{f_i p_j}^{sd1} / M^{su} \right\rceil \\ &\quad + \textstyle\sum_j \left[e^{sC} \sum_i b_{f_i p_j}^{sd1} + e^{sP} \beta^{sC} (1 - \delta_j^s) \sum_i b_{f_i p_j}^{sd1}\right] \\ &\quad + \textstyle\sum_j \sum_k \left[(e^0 + \alpha M^{sp}) \cdot D_{p_j b_k} + e^0 D_{p_j b_k}\right] \left\lceil b_{p_j b_k}^{sd1} / M^{sp} \right\rceil \\ &\quad + \textstyle\sum_k \left[e^{sH} \beta^{sL} \sum_j b_{p_j b_k}^{sd1} + e^{sF} \beta^{sH} \beta^{sL} \sum_j b_{p_j b_k}^{sd1}\right] \end{aligned} \tag{2}$$

where ⌈⌉ is the ceiling function. In (1), C^{sd1} is the total cost when corn stover is used as the feedstock in biofuel manufacturing, it can be calculated by (3).

$$C^{sd1} = \sum_k C_k^{sd1} \tag{3}$$

where C_k^{sd1} is the cost incurred in bioethanol production using preprocessed corn stover at bio-refinery plant k, which can be calculated by (4). It consists of the cost for purchasing preprocessed corn stover by bio-refinery plant k from preprocessing centers, the cost for transporting preprocessed corn stover from preprocessing centers to bio-refinery plant k, the cost for the corn stover bioconversion (i.e., hydrolysis and fermentation) at bio-refinery plant k, and the inventory cost for holding the raw material of preprocessed corn stover at bio-refinery plant k. Note that $1/d$ is the fraction of the yearly production demand of preprocessed corn stover, which specifies the inventory level of the raw materials for the bio-refinery plants (i.e., $1/d$ yearly production demand of stover needs to be kept as the inventory).

$$C_k^{sd1} = \sum_j z_j b_{p_j b_k}^{sd1} + \sum_j \lceil b_{p_j b_k}^{sd1}/M^{sp} \rceil D_{p_j b_k} T_{p_j b_k}^{sp} + o^{sH}\beta^{sL} \sum_j b_{p_j b_k}^{sd1} + o^{sF}\beta^{sH}\beta^{sL} \sum_j b_{p_j b_k}^{sd1} + \frac{h^{sp}}{d} \sum_j b_{p_j b_k}^{sd1} \quad (4)$$

Correspondingly, the cost per unit of bioethanol produced at bio-refinery plant k can be obtained by (5).

$$PP_k^{sd1} = C_k^{sd1}/TP_k^{sd1} \quad (5)$$

where TP_k^{sd1} is the total bioethanol produced in gallons using preprocessed corn stover at bio-refinery plant k, which can be calculated by (6).

$$TP_k^{sd1} = \sigma_k^s \sum_j b_{p_j b_k}^{sd1} \quad (6)$$

The constraints are formulated as follows.

$$PP_k^{sd1} \leqslant PP_k^c, \ \forall\, k \quad (7)$$

$$\sum_j b_{f_i p_j}^{sd1} \leqslant Q_i, \ \forall\, i \quad (8)$$

$$\sum_i b_{f_i p_j}^{sd1} \leqslant y_j^{sd1}, \ \forall\, j \quad (9)$$

$$\sum_k b_{p_j b_k}^{sd1} \leqslant \beta^{sP}\beta^{sC}(1-\delta_j^s) y_j^{sd1}, \ \forall\, j \quad (10)$$

$$\sum_j b_{p_j b_k}^{sd1} \leqslant W_k^s, \ \forall\, k \quad (11)$$

$$NPV_j^{sd1} > 0, \ \forall\, j \quad (12)$$

$$b_{f_i p_j}^{sd1},\ b_{p_j b_k}^{sd1},\ y_j^{sd1} \geqslant 0 \quad (13)$$

$$x_j^{sd1} \in \{0, 1\} \quad (14)$$

$$b_{f_i p_j}^{sd1} \leqslant N x_j^{sd1}, \ \forall\, i, \ \forall\, j \quad (15)$$

$$b_{p_j b_k}^{sd1} \leqslant N x_j^{sd1}, \ \forall\, j, \ \forall\, k \quad (16)$$

$$y_j^{sd1} \leqslant N x_j^{sd1}, \ \forall\, j \quad (17)$$

$$\sum_k TP_k^s = D \quad (18)$$

$$x_j^{sd1} \leqslant N y_j^{sd1}, \ \forall\, j \quad (19)$$

$$y_j^{sd1} \leqslant K, \ \forall\, j \quad (20)$$

Constraint (7) specifies the economic feasibility of using preprocessed corn stover instead of milled corn in bioconversion by bio-refinery plant k. Constraint (8) illustrates that the corn stover supply capacity at each farm should not be violated. Constraint (9) shows that the total amount of incoming corn stover from various farms cannot be larger than the designed capacity in terms of handling corn stover at preprocessing center j. Constraint (10) demonstrates that the total amount of preprocessed corn stover sold by preprocessing center j cannot be larger than the maximum production capacity of preprocessed corn stover considering the process efficiencies of both chemical pretreatment and physical densification as well as the secondary products of animal feed after chemical pretreatment. Constraint (11) denotes that the total amount of preprocessed corn stover purchased by each bio-refinery plant cannot exceed its corresponding preprocessed corn stover processing capacity. In (12), NPV_j^{sd1} is the net present value of the project of building and running preprocessing center j throughout its lifetime. It requires that the net present value be larger than zero. Constraint (13) shows the non-negativity constraints for the decision variables of the preprocessing center capacities and material flows. Constraint (14) demonstrates that the decision variable x_j^{sd1} is binary. Constraint (15) ensures that the transportation amount from farm i to preprocessing center j is set to zero if preprocessing center j is not

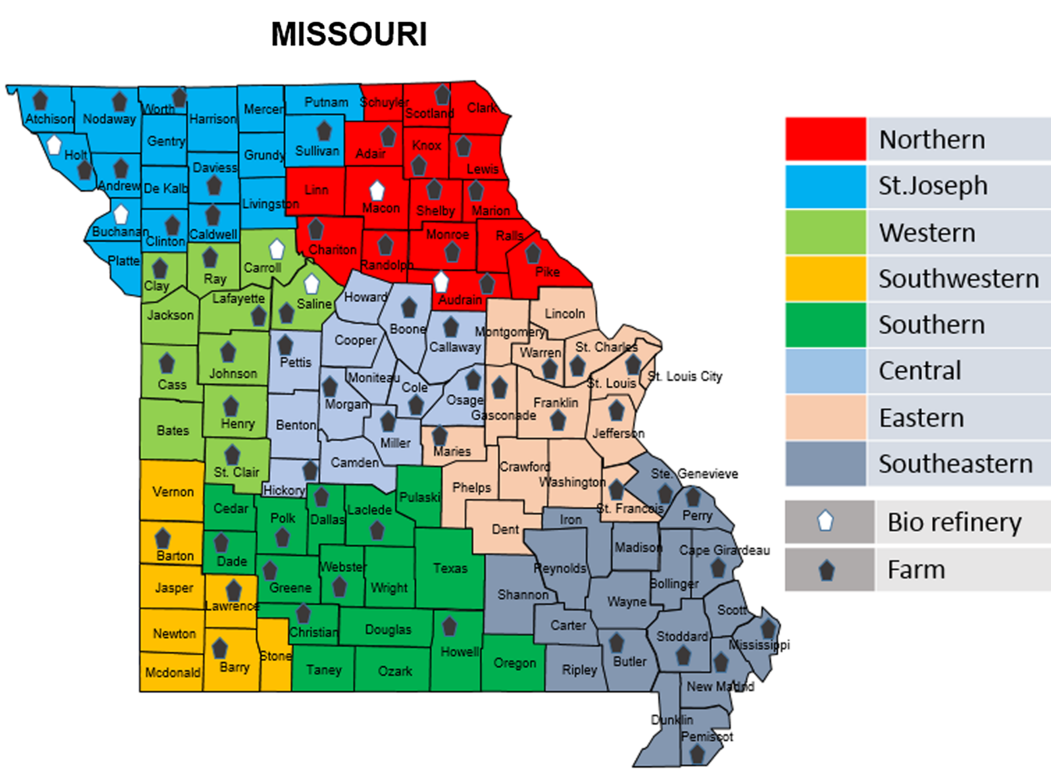


Fig. 2. Farms and bio-refinery plants in Missouri [74].

Table 5
Location and annual capacity of bio-refinery plants in Missouri.

Bio-refinery code #	Plant	County	Latitude	Longitude	Yearly capacity (in Million gallons of bioethanol)	Yearly capacity (in tons of corn)	Yearly capacity (in tons of corn stover)
1	POET Bio-refining	Macon	39.75	−92.38	46	469,388	460,000
2	Golden Triangle Energy Cooperative	Holt	40.19	−95.44	20	204,082	200,000
3	Mid Missouri Energy	Saline	39.2	−93.38	50	510,204	500,000
4	POET Bio-refining	Audrain	39.25	−91.65	50	510,204	500,000
5	ICM Biofuels	Buchanan	39.74	−94.85	50	510,204	500,000
6	Show Me Ethanol, LLC	Carroll	39.36	−93.45	60	612,245	600,000

selected. Constraint (16) ensures that the transportation amount from preprocessing center j to bio-refinery plant k is set to zero if preprocessing center j is not selected. Constraint (17) ensures that the capacity of preprocessing center j is set to zero if preprocessing center j is not selected. Constraint (18) ensures that the overall production of bioethanol can satisfy the total demand. Constraint (19) prevents the capacity of preprocessing center j being zero when location j is selected for building the preprocessing center. Constraint (20) limits the annual handling capability of corn stover of preprocessing center j to a maximum capacity according to existing technological capability.

In (12), NPV_j^{sd1} can be calculated by (21).

$$NPV_j^{sd1} = -CS_j^{sd1} + \sum_{t=3}^{T+2} \frac{\text{Profit}_j^{sd1}}{(1+r)^t} \tag{21}$$

In (21), CS_j^{sd1} is the discounted setup cost of preprocessing center j. It can be calculated by (22).

$$CS_j^{sd1} = (I_j^{sd1}/3) + (2I_j^{sd1}/3(1+r)) \tag{22}$$

where I_j^{sd1} is the total initial setup cost of preprocessing center j. It consists of the setup costs for both chemical pretreatment (AFEX) and physical densification, which can be calculated by (23). Typically, the first two years are used to build the preprocessing center from scratch. One third of the initial investment is required in the first year and the remaining two thirds are required in the second year [13]

$$I_j^{sd1} = [(a^{sC} y_j^{sd1}) + x_j^{sd1} b^{sC}] + G^P \cdot \{[y_j^{sd1} \beta^{sC}(1-\delta_j^s)]/g^P\} \tag{23}$$

In (21), Profit_j^{sd1} is the yearly profit of preprocessing center j which is assumed to be fixed throughout the lifetime based on the current demand of biofuel. It can be calculated by subtracting the cost of purchasing corn stover by preprocessing center j, the cost of corn stover transportation between farms and preprocessing center j, and the operational cost of preprocessing center j from the yearly revenue of the preprocessing center j. It can be calculated by (24).

$$\begin{aligned}\text{Profit}_j^{sd1} = {} & z_j^{sd1} \textstyle\sum_k b_{p_j b_k}^{sd1} + F_j \delta_j^s \beta^{sC} \sum_i b_{f_i p_j}^{sd1} - \sum_i P_i^s b_{f_i p_j}^{sd1} \\ & - \textstyle\sum_i [b_{f_i p_j}^{sd1}/M^{su}] D_{f_i p_j} T_{f_i p_j}^{su} \\ & - o^{sC} \textstyle\sum_i b_{f_i p_j}^{sd1} - o^{sP} \beta^{sC}(1-\delta_j^s) \sum_i b_{f_i p_j}^{sd1}\end{aligned} \tag{24}$$

Note that, the raw material inventory cost for holding corn stover at preprocessing center is not considered. The literature foresees that third party supply harvesters will enter into the existing biofuel supply chain, offering the service of corn stover harvesting and storage to enhance a steady supply of feedstock [63,64] with a relatively low storage cost for holding baled corn stover [65]. The selling price of corn stover from farms typically includes the storage cost [66]. This implies that the inventory of corn stover at preprocessing centers can be managed by a Vendor Managed Inventory (VMI), and thus the inventory holding cost is not included in (24). For the bio-refinery plant in distributed supply chain model, the raw material inventory of preprocessed stover is considered as shown in (4) since the bio-refinery plant is further away from the farms in the distributed supply chain compared to the preprocessing center and the uncertainty of supply may be augmented. This assumption also holds for the pathway 2 model.

3.2.2. Pathway 2: Densification at preprocessing centers and AFEX at bio-refinery plants

In this section, the formulation of the corn stover-sourced distributed biofuel supply chain built by pathway 2 is introduced (for simplicity, this model is referred to as pathway 2 supply chain in the remainder of the paper). In this model, the physical densification is implemented at the newly constructed preprocessing center while AFEX is carried out at existing bio-refinery plants. Note that the superscript "*sd2*" is used to denote the notations used in the pathway 2 supply chain. The objective can be similarly formulated as (25).

$$\min_{x_j^{sd2}, y_j^{sd2}, b_{f_i p_j}^{sd2}, b_{p_j b_k}^{sd2}} w_1 E^{sd2} + w_2 C^{sd2} \tag{25}$$

Similarly, E^{sd2} can be calculated by (26).

$$\begin{aligned}E^{sd2} = {} & \textstyle\sum_i \sum_j [(e^0 + \alpha M^{su}) \cdot D_{f_i p_j} + e^0 D_{f_i p_j}][b_{f_i p_j}^{sd2}/M^{su}] + \sum_j [e^{sP} \sum_i b_{f_i p_j}^{sd2}] \\ & + \textstyle\sum_j \sum_k [(e^0 + \alpha M^{sp}) \cdot D_{p_j b_k} + e^0 D_{p_j b_k}][b_{p_j b_k}^{sd2}/M^{sp}] \\ & + \textstyle\sum_k [e^{sC} \sum_j b_{p_j b_k}^{sd2} + e^{sH} \beta^{sL} \beta^{sC} \sum_j b_{p_j b_k}^{sd2} + e^{sF} \beta^{sH} \beta^{sL} \beta^{sC} \sum_j b_{p_j b_k}^{sd2}]\end{aligned} \tag{26}$$

Note that processing emissions include AFEX, hydrolysis, and fermentation at bio-refinery plants. In (25), C^{sd2} can be calculated by (27)

$$C^{sd2} = \sum_k C_k^{sd2} \tag{27}$$

where C_k^{sd2} is the annual cost at bio-refinery plant k that considers the annualized AFEX setup cost, densified corn stover purchase cost by bio-refinery plant k from preprocessing centers, densified corn stover transportation cost from preprocessing centers to bio-refinery plant k,

Table 6
Conditions for hydrolysis and fermentation of corn and corn stover.

Process	Substrate	Enzyme	loading	pH	Temp (degree centigrade)	Reference
Hydrolysis	Corn	α-Amylase	Broth contains 1 gm KH_2PO_4 and 200 μL high temperature α-Amylase, Liquozyme, at 1.26 g/mL, per liter	4.2	60–70	[81]
	Corn stover	Accelerase 1500	0.5 mL/g cellulose	–	50	[81]
Fermentation	Corn, corn-stover	Saccharomyces cerevisiae	–	5.5	30	[82]

Table 7
Conditions for AFEX pretreatment and densification processes.

Process	Substrate	Input	Process 1	Output	Process 2	Output	Reference
AFEX	Corn stover (loose or pelletized)	Pressure = 20 atms.; temp = 20 degree centigrade	AFEX reactor (90 degree centigrade, 20 atms. Pressure)	Pretreated corn stover slurry	Ammonia column (pressure = 3 atms., top temperature = 28 degree centigrade; bottom temperature = 135 degree centigrade)	Dry pretreated corn stover	[13]
Densification	Corn stover	Density = 200 kg/m3	Grinding, drying, hammer milling	Corn stover with particle size = 2 mm	Pelleting	Density = 700 kg/m3	[9,62]

operational costs including AFEX, hydrolysis, and fermentation, and raw material inventory holding cost to hold the densified corn stover. It is calculated by (28).

$$C_k^{sd2} = G_C^{sd2}\left[\frac{r}{1-(1+r)^{-(T+1)}}\right] + \sum_j z_j^{sd2} b_{p_jb_k}^{sd2} + \sum_j [b_{p_jb_k}^{sd2}/M^{sp}] D_{p_jb_k} T_{p_jb_k}^{sp} \\ + o^{sC}\sum_j b_{p_jb_k}^{sd2} + o^{sH}\beta^{sL}\beta^{sC}\sum_j b_{p_jb_k}^{sd2} + o^{sF}\beta^{sH}\beta^{sL}\beta^{sC}\sum_j b_{p_jb_k}^{sd2} \\ + \frac{h^{sp}}{d}\sum_j b_{p_jb_k}^{sd2} \tag{28}$$

Note that in (28), unlike in the pathway 1 supply chain where the setup of the preprocessing center takes two years since it is built from scratch, here, the AFEX system is intended to be built in existing bio-refinery plant with available infrastructure and facilities, thus, we assume the setup time is one year.

In (28), G_C^{sd2} is the setup cost for the AFEX system, which can be calculated by (29). The capacity of the AFEX system is determined by the capacity of the corresponding bio-refinery plants.

$$G_C^{sd2} = (a^{sC}(W_k^s/\beta^{sC})) + b^{sC} \tag{29}$$

The cost per gallon of bioethanol produced through corn stover following pathway 2 in bio-refinery plant k can be obtained by (30).

$$PP_k^{sd2} = C_k^{sd2}/TP_k^{sd2} \tag{30}$$

where TP_k^{sd2} is the total gallons of bioethanol produced using pre-processed corn stover at bio-refinery plant k, which can be calculated by (31).

$$TP_k^{sd2} = (\beta^{sC}\sigma_k^s)\sum_j b_{p_jb_k}^{sd2} \tag{31}$$

The constraints are formulated in detail in Appendix B. Most of these constraints are similar to the ones in pathway 1 except the NPV calculation and the selling capacity of preprocessed corn stover since only physical densification is included in the preprocessing center and animal feed being sold back is not considered.

3.3. Corn stover-sourced biofuel supply chain using centralized preprocessing strategy

In this section, we establish the model to estimate the cost and emission per gallon of bioethanol produced in bio-refinery in a corn stover-sourced AFEX centralized biofuel supply chain (for simplicity, this model is referred to as centralized AFEX supply chain in the remainder of the paper). A superscript "*sc*" is used to denote the corresponding notations used in this model. The objective can be similarly formulated by (32). The decision variable is the transportation quantity of corn stover from farm j to bio-refinery plant k.

$$\min_{b_{f_ib_k}^{sc}} w_1E^{sc} + w_2C^{sc} \tag{32}$$

In (32), E^{sc} is the total emissions incurred, which can be calculated by (33). It includes the emissions incurred by corn stover transportation from various farms to bio-refinery plants and corn stover processing through pretreatment, hydrolysis and fermentation at bio-refinery plants.

$$E^{sc} = \sum_i\sum_k [(e^0 + \alpha M^{su})\cdot D_{f_ib_k} + e^0 D_{f_ib_k}][b_{f_ib_k}^{sc}/M^{su}] \\ + \sum_k [e^{sC}\sum_i b_{f_ib_k}^{sc} + e^{sH}\beta^{sL}\beta^{sC}\sum_i b_{f_ib_k}^{sc} + e^{sF}\beta^{sH}\beta^{sL}\beta^{sC}\sum_i b_{f_ib_k}^{sc}] \tag{33}$$

In (32), C^{sc} is the total cost, which can be calculated by (34).

$$C^{sc} = \sum_k C_k^{sc} \tag{34}$$

where C_k^{sc} is the annual cost at bio-refinery plant k that includes annualized AFEX setup cost, corn stover purchase cost by bio-refinery plant k from farm i, corn stover transportation cost from farm i to bio-refinery plant k, and the operational costs including AFEX, hydrolysis,

Table 8
Setup costs and emissions of physical and chemical preprocessing.

Process	Setup cost	Reference	Emission (lbs. of CO_2/ton)	Reference
Grinding	\$23,134/machine	[93]	8.8	[83,84]
Drying	\$4570/machine	[93]	17.05	[84,94]
Hammer-milling	\$14,737/machine	[93]	11.16	[84,93]
Pelleting	\$45,010/machine	[93]	136	[63,84]
AFEX	a^{sC} = \$14.8375/(ton/year/machine); b^{sC} = \$5.225 × 10^6/machine	[13,93]	341.25	[13,84,95]

and fermentation. It is calculated by (35).

$$C_k^{sc} = [(a^{sC}(W_k^s/\beta^{sC})) + b^{sC}]\left[\frac{r}{1-(1+r)^{-(T+1)}}\right] + \sum_i P_i^s b_{f_i b_k}^{sc} + \sum_i \lceil b_{f_i b_k}^{sc}/M^{su} \rceil D_{f_i b_k} T_{f_i b_k}^{su} + o^{sC}\sum_i b_{f_i b_k}^{sc} + o^{sH}\beta^{sL}\beta^{sC}\sum_i b_{f_i b_k}^{sc} + o^{sF}\beta^{sH}\beta^{sL}\beta^{sC}\sum_i b_{f_i b_k}^{sc} \tag{35}$$

Note that, inventory cost for holding raw materials of corn stover is not considered in (35) since bio-refinery plants in this centralized supply chain model are located immediately downstream of the farms, the raw material inventory holding can be similarly managed by VMI through the involvement of third party harvesting and storage service providers.

The constraints for this model include economic feasibility for each bio-refinery plant, corn stover supply capability of each farm, bio-refinery plant biomass handling capability, non-negativity of transportation amount, and total biofuel demand satisfaction. The details of these constraints are formulated in Appendix C.

4. Case study

The effectiveness of the proposed corn stover-sourced supply chain model considering two restructuring strategies will be examined using the relevant data of the state of Missouri in the United States. In this section, all the input data used in the case study are introduced. Missouri is located on the "corn belt" in the Midwest of the United States. Approximately 18 million tons of corn is produced in the state each year [67]. It ranks 3rd and 13th in biodiesel and bioethanol production capacities, respectively, in the United States [68].

4.1. Corn and corn stover supply from farms

The data of the corn and corn stover supply in Missouri is obtained from National Agricultural Statistics Service (NASS) provided by the U.S. Department of Agriculture [69]. There are 63 out of a total of 115 counties planting corn in Missouri. Each county is modeled as a pseudo "farm" providing corn and corn stover to the biofuel supply chain. The latitude and longitude of the center of each county is used to approximate the location of each pseudo "farm". Note that this "centralization" assumption has been widely used in literature [24,64] for simplifying the model. To offset the possible error of this assumption, a tortuosity factor is typically used to adjust the physical distance [7,70]. So in this paper, we use a tortuosity factor with the value of 1.27 to obtain the adjusted transportation distance to deal with the possible errors due to using this "centralization" assumption [70].

The literature has indicated that a stable and continuous biomass supply is a complex process influenced by different factors (i.e., willingness, coordination, supply reliability, participation, and economic context) [64]. Complex interplays exist among these five factors under four different coordination scenarios [64]. However, it's hard to quantitatively capture the complicated correlations among the five factors so that the variations of biomass supply and price can be quantified. Therefore, in this paper, we consider the variations of the supply and price of corn and corn stover from historical records in the past five years [66] to model and examine such uncertainties. Specifically, the corn and corn stover supplies of each county are randomly drawn from a uniform distribution with the mean value equal to the average of the past five years and a bandwidth of 22% in both directions [66]. Here we assume that the corn stover supply is the same as corn supply [56]. The corn selling price is drawn from another uniform distribution with mean of \$180/ton that is equal to the average of the past five years and a bandwidth of 5% in both directions, i.e., \$171–\$189/ton [58,63]. The average price of corn stover after taking into account the corn stover collection and storage cost using a three-pass harvesting system is \$60/ton [71], and it is expected to fluctuate between \$55 and \$65 per ton [11,25,71].

The mean of the annual supply capacity of corn and corn stover and the farm locations in Missouri are summarized in Table 4. The counties with corn planting and corresponding corn supply quantity are extracted from [69]. The latitude and longitude of the center of each county are identified by [35]. The available corn stover supply is 60% of total corn stover [56,62]. The selling price of AFEX chemically pretreated corn stover that is sold back to farms as animal feed is set at \$171/ton [72].

4.2. Bio-refinery plant

There are six bio-refinery plants in Missouri with yearly capacities from 20 to 60 million gallons of bioethanol per year [73]. The locations of these bio-refinery plants as well as of the farms where corn is planted

Table 9
Transportation costs and emission related parameters.

	Distance range (mile)	Cost for corn and corn stover pellets (\$ per mile per truck)	Cost for corn stover (\$ per mile per truck)	Reference
Transportation cost	Less than 25	3.12	1.74	[88]
	Between 25 and 100	5.72	3.19	
	More than 100	7.8	4.35	
	Parameter	**Value**		**Reference**
Transportation emission	e^0	4.44 lbs. of CO_2/mile		[62,96,97]
	α	0.074 lbs. of CO_2/mile/ton		
	M^c	55.75 tons		
	M^{su}	22.3 tons		
	M^{sp}	55.75 tons		

Table 10
Performance of the corn sourced supply chain.

	Total cost ($)	Total emission (lbs. of CO_2)	Total production of the supply chain (gal)	Cost per unit production ($)	Emission per unit production (lbs. of CO_2 /gal)
Mean	603,567,475	4,891,616,936	262,531,000	2.30	18.63
Half width of 95% CI	508,281	204,338	–	0.002	0.001

Table 11
Performance of the corn stover sourced distributed supply chain in pathway 1.

	Total cost ($)	Total emission (lbs. of CO_2)	Total production of the supply chain (gal)	Cost per unit production ($)	Emission per unit production (lbs. of CO_2/gal)
Mean	543,852,062	6,853,317,839	262,531,000	2.07	26.10
Half width of 95% CI	258,203	345,213	–	0.001	0.00034
Reduction Compared to corn-based supply chain	9.8%	−38%	–	10%	−37%

in the state of Missouri are shown in Fig. 2 [74]. The location and capacity of each plant is given in Table 5 [75–80]. Parameters for the hydrolysis and fermentation in bio-refinery plants are summarized in Table 6 [81,82]. The operating cost of corn milling is $8.5/ton [83]. The emissions from corn milling are 17.05 lbs. CO_2/ton [84,85].

4.3. Bioethanol demand

The total biofuel demand in Missouri was 308.86 million gallons in 2015, which was roughly 20% of the total gasoline demand [86]. Most of the biofuel demand is assumed to be satisfied by E85 [75], which consists of 85% bioethanol and 15% gasoline by volume. Thus, the total bioethanol demand in Missouri is 262.5 million gallons. The bioethanol yield from one ton of corn is 98 gallons [87], which can be translated into annual demand for milled corn of 2.678 million tons. The bioethanol yield from one ton of chemically pretreated and physically densified corn stover is set at 100 gallons, since the corn stover ethanol yield ranges from 70 to 130 gallons/ton in literature [88–92]. It can be translated into annual demand for preprocessed corn stover of 2.625 million tons.

4.4. Preprocessing centers

Each corn planting county is considered a candidate location for a preprocessing center, since the preprocessing centers are typically cooperative financial institutions held by farmers [13]. The latitude and longitude of the center of each county is used to approximately represent the location of each candidate. The lifetime of the preprocessing centers of both pathways is 25 years [59,60]. Typical technical parameters of AFEX and densification are summarized in Table 7 for illustration [9,13,62].

Table 13
Average financial performance of a 70,000 tons/year preprocessing center in the pathway 1 supply chain.

Parameter	Value
AFEX setup cost ($)	6,234,544
Physical densification setup cost ($)	1,487,500
Total setup cost ($)	7,722,044
Revenue per year ($)	10,803,743
Processing cost per year ($)	5,628,918
Transportation cost per year ($)	157,364
Raw material cost per year ($)	3,721,419
Profit per year ($)	1,296,042

The selling price of chemically and physically preprocessed corn stover at a preprocessing center in pathway 1 is $175/ton [25]. The selling price of physically preprocessed corn stover at a preprocessing center in pathway 2 is $95/ton [25,92]. The AFEX pretreatment in pathway 2 is assumed to be built at each of the six existing bio-refinery plants in Missouri. We assume a mass conversion efficiency of 95% for both chemical pretreatment and physical densification.

For pathway 1, 25% corn stover pretreated in AFEX will be transferred to secondary products and sold back as animal feed to the farms

Table 12
Optimal average preprocessing center capacities in the pathway 1 supply chain.

County Code #	Capacity* (tons/day)	Half width of 95% CI	County Code #	Capacity* (tons/day)	Half width of 95% CI	County Code #	Capacity* (tons/day)	Half width of 95% CI	County Code #	Capacity* (tons/day)	Half width of 95% CI
1	70,000	–	17	70,000	–	33	0		49	70,000	–
2	70,000	–	18	70,000	–	34	67,480	1146	50	0	
3	70,000	–	19	70,000	–	35	67,900	1049	51	68,002	1015
4	70,000	–	20	70,000	–	36	70,000	–	52	0	
5	70,000	–	21	70,000	–	37	70,000	–	53	67,076	1028
6	70,000	–	22	70,000	–	38	70,000	–	54	60,550	2043
7	70,000	–	23	70,000	–	39	70,000	–	55	68,022	1015
8	70,000	–	24	70,000	–	40	70,000	–	56	0	
9	70,000	–	25	70,000	–	41	70,000	–	57	0	
10	70,000	–	26	70,000	–	42	70,000	–	58	66,808	1024
11	70,000	–	27	70,000	–	43	0		59	63,288	1166
12	70,000	–	28	70,000	–	44	58,026	1,089	60	70,000	–
13	70,000	–	29	70,000	–	45	70,000	–	61	64,402	1134
14	70,000	–	30	70,000	–	46	60,841	1,007	62	58,616	989
15	70,000	–	31	0		47	26,691	2,983	63	70,000	–
16	70,000	–	32	70,000	–	48	70,000	–			

* Zero capacity means the county is not selected to build a preprocessing center.

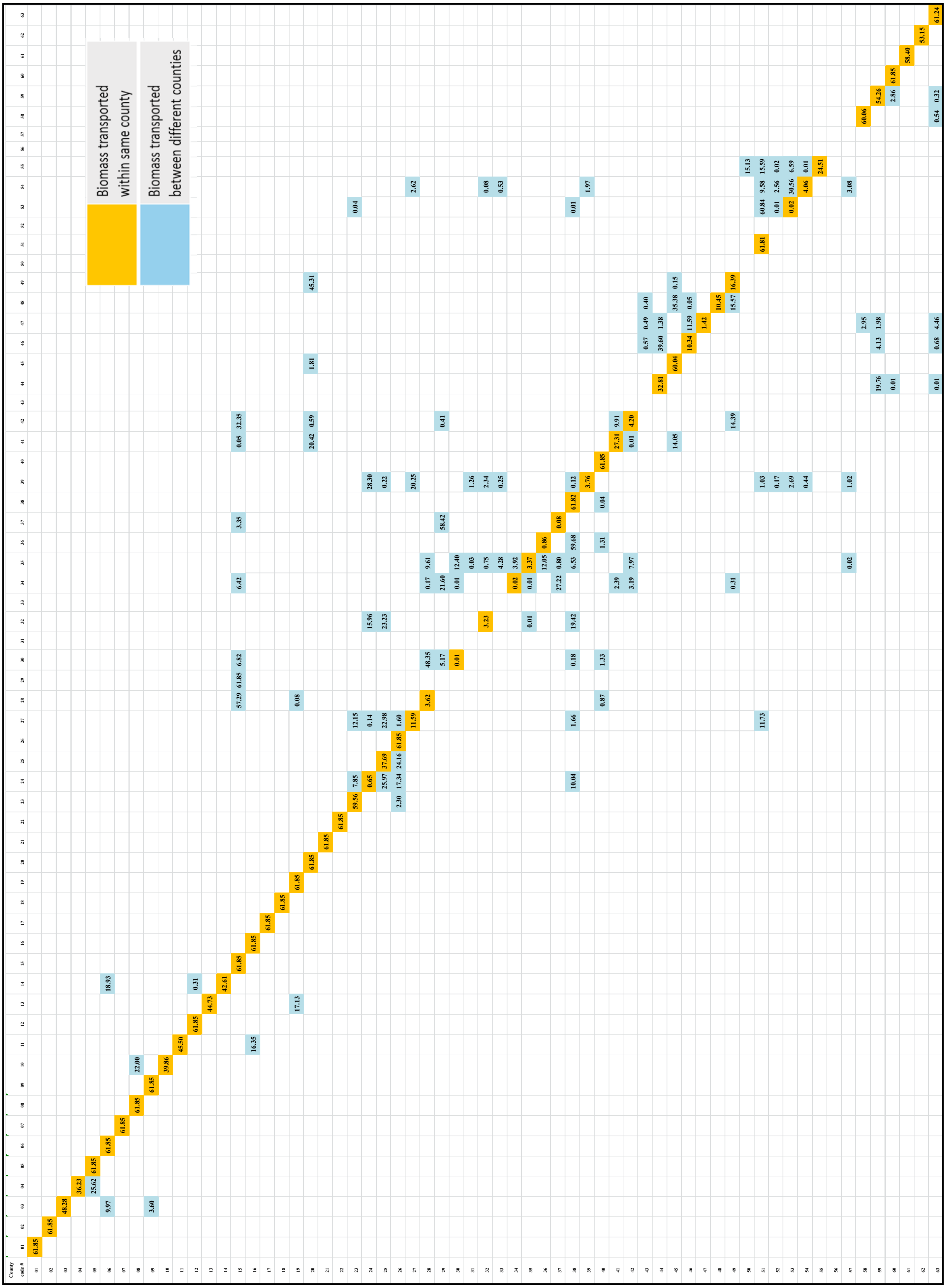


Fig. 3. Average corn stover transportation amount from farms to preprocessing centers in kilo-tons in the pathway 1 supply chain.

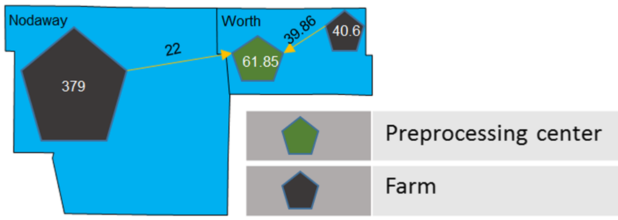


Fig. 4. Worth county sourcing the surplus demand.

[13]. The setup costs (including both capital and installation) and emissions for the different processes involved in the physical and chemical preprocessing of biomass are shown in Table 8.

The operating cost (including maintenance and taxes) of AFEX is \$69.77/ton of corn stover [93]. The physical densification system usually consists of grinding, drying, hammer milling, and pelleting equipment, the typical capacity of such equipment is 1.5 ton/hr [95]. Assuming 2800 working hours in a year, g_p is set to be 4200 tons per year. The operating cost (including maintenance and taxes) of physical densification is \$29.8/ton [93].

4.5. Transportation

The transportation cost and emission related parameters are listed in Table 9.

5. Results and analysis

In this section, the results of the case study using the Missouri data for all three models from two different supply chain restructuring strategies are presented. Also, the sensitivity analysis is conducted to examine the variations of the model performance due to the variations of the input parameters. Finally, the performance difference between the three models is discussed.

5.1. Results

5.1.1. Corn-sourced scenario

In the corn-sourced supply chain, the total demand of bioethanol in Missouri is proportionally allocated to each of the six bio-refinery plants according to respective capacities. Similarly, the demand for corn in each bio-refinery plant is proportionally allocated to each of the 63 farms in Missouri, according to the capacity of each farm [75]. 500 replications are run with different prices and supplies of the corn from various farms. The resultant cost and emissions are illustrated in Table 10. The average unit cost is \$2.30 per gallon. It falls in the estimation range of the unit cost for corn based bioethanol production (i.e., \$1.89–\$3.59 per gallon) [24].

5.1.2. Pathway 1 supply chain (quality depot)

The maximum capacity of the preprocessing center is 70,000 tons/year [93]. Equal weights for both objectives are used (i.e., w_1 and w_2 are set as 0.5). 500 replications with different prices and supplies of the corn stover from various farms is run to solve the proposed corn stover-sourced distributed biofuel supply chain problem formulated in pathway 1. The resultant cost and emission of the supply chain are illustrated in Table 11. As can be seen through comparison with Table 10, the cost per unit production is reduced by 10%, while the emission per unit production has a significant increase of 37%. Note that in Section 6.2, a discussion is given over the emissions' variations

Table 14
Average preprocessed corn stover transported from preprocessing center to bio-refinery plants in the pathway 1 supply chain (kilo-tons).

	Biorefinery code #							Biorefinery code #					
	1	2	3	4	5	6		1	2	3	4	5	6
County Code #							County Code #						
1					47.4		33						
2		47.4					34			47.4			
3					47.4		35			47.4			
4					47.4		36			47.4			
5					47.4		37						47.4
6					47.4		38						47.4
7		47.4					39			47.4			
8		47.4					40						47.4
9					44.1	3.3	41				47.4		
10					47.4		42				47.4		
11	47.4						43						
12						47.4	44				35.2		
13						47.4	45				47.4		
14						47.4	46				43.6		
15	47.4						47				45.7		
16	47.4						48				47.4		
17	47.4						49				47.4		
18	47.4						50						
19	47.4						51					47.4	
20	47.4						52						
21	47.4						53						47.4
22	47.4						54			47.4			
23					47.4		55			47.4			
24						47.4	56						
25						47.4	57						
26						47.4	58			47.4			
27						47.4	59				47.4		
28						47.4	60				47.4		
29	33.6					13.8	61			36.1			11.3
30			47.4				62			37.5			
31							63				43.9		3
32			47.4										

Table 15
Optimal average preprocessing center capacities in the pathway 2 supply chain.

County Code #	Capacity* (tons/day)	Half width of 95% CI	County Code #	Capacity* (tons/day)	Half width of 95% CI	County Code #	Capacity* (tons/day)	Half width of 95% CI	County Code #	Capacity* (tons/day)	Half width of 95% CI
1	52,500	–	17	52,500	–	33	14,243	215	49	52,500	–
2	52,500	–	18	52,500	–	34	52,500	–	50	17,208	197
3	52,500	–	19	52,500	–	35	52,500	–	51	52,500	–
4	52,500	–	20	52,500	–	36	52,500	–	52	4,313	78
5	52,500	–	21	52,500	–	37	52,500	–	53	52,500	–
6	52,500	–	22	52,500	–	38	52,500	–	54	52,500	–
7	52,500	–	23	52,500	–	39	52,500	–	55	52,500	–
8	52,500	–	24	52,500	–	40	52,500	–	56	3,144	34
9	52,500	–	25	52,500	–	41	52,500	–	57	5,670	284
10	52,500	–	26	52,500	–	42	52,500	–	58	52,500	–
11	52,500	–	27	52,500	–	43	52,496	8	59	52,500	–
12	52,500	–	28	52,500	–	44	52,500	–	60	0	
13	52,500	–	29	52,500	–	45	52,500	–	61	0	
14	52,500	–	30	52,500	–	46	52,500	–	62	0	
15	52,500	–	31	52,463	47	47	36,650	897	63	45,651	843
16	52,500	–	32	52,500	–	48	52,500	–			

* Zero capacity means the county is not selected to build a preprocessing center.

when expanding the model scope to include the redundant corn stover handling.

On average, 56 counties are selected for building the preprocessing centers with respective capacities. Table 12 shows the resultant locations selected and the corresponding average capacities across all the replications. Most of the selected counties are selected to build a preprocessing center with capacity equal to or very close to the capacity upper bound. The results in terms of the county selection and the capacity are fairly consistent across all the replications. For example, the preprocessing center at Barton County (county code 51) has been selected with maximum capacity in more than 95% of the replications. Andrew County (county code 1) has been selected with the maximum capacity in all the replications.

The counties that are not selected by the model for building preprocessing centers typically have a low corn stover supply capacity and are surrounded by other low stover supply counties. Dallas County (County code 31) is an example. The farm capacity is 1.3 kilo-tons, and it is surrounded by Hickory (County code 32, farm capacity 6.6 kilo-tons), Polk (County code 39, farm capacity 5.8 kilo-tons), Greene (County code 54, farm capacity 4.6 kilo-tons), Webster (County code 57, farm capacity 4.2 kilo-tons), and Laclede (County code 33, farm capacity 5.2 kilo-tons) counties.

The details of financial performance of a typical preprocessing center with capacity of 70,000 tons/year built in Sullivan County (County code 14) are provided in Table 13. Note that the AFEX setup cost and physical densification setup cost are calculated using (23) along with the y_j and x_j in Table 12 and the parameters with respect to the setup cost of AFEX and physical densification equipment (grinding, drying, hammer milling, and pelleting) shown in Table 11. The revenue, processing cost, transportation cost, raw material cost, and profit are calculated using (24).

As can be seen from Table 13, the transportation cost is much less than the processing cost and the raw material cost. This can be largely explained by the amount (in kilo-tons) and pattern of transportation between the farms and the preprocessing centers as shown in Fig. 3.

Table 17
Average financial performance of a 52,500 tons/year preprocessing center intended to be built in the pathway 2 supply chain.

Parameter	Value
Physical densification setup cost ($)	1,137,500
Revenue per year ($)	4,738,125
Processing cost per year ($)	1,422,273
Transportation cost per year ($)	194,981
Raw material cost per year ($)	2,675,672
Profit per year ($)	445,199

Most of the biomass produced by the farm is supplied to the preprocessing center built in the same county. This is because the model tries to keep the transportation cost and emissions at the minimum by sourcing most of the biomass locally.

In cases, where the selected preprocessing center has exhausted the corn stover supply from the farm in the same county, it sources the balance from the counties which have surplus supply with a lower cost (highlighted in blue in Fig. 3). For example, as shown in Fig. 4, the preprocessing center in Worth County (County code 10) first utilizes around 40 kilo-tons of corn stover available from the farm located in the same county, and then sources the remaining from the farm in the neighboring Nodaway County (County code 8) which has a surplus supply with a capacity of 379 kilo-tons as well as a shorter transportation distance.

The average transportation amounts in kilo-tons between the preprocessing centers and the bio-refinery plants are illustrated in Table 14. Most of the preprocessing centers serve a single bio-refinery plant or at most two bio-refinery plants, depending on capacity, geographical proximity, and the demand of the bio-refinery plant. The bio-refinery plant with the lowest production capacity (bio-refinery plant 2, 20 million gallons per year) sources the preprocessed biomass from three preprocessing centers. The bio-refinery plant with the highest production capacity (bio-refinery plant 6, 60 million gallons per year)

Table 16
Performance of the pathway 2 supply chain.

	Total cost ($)	Total emission (lbs. of CO_2)	Total production of the supply chain (gal)	Cost per unit production ($)	Emission per unit production (lbs. of CO_2 /gal)
Mean	556,882,330	6,604,038,135	262,531,000	2.12	25.16
Half width of 95% CI	302,236	428,362	–	0.004	0.0002
Reduction compared to corn-based supply chain	7.7%	−35.1%	–	7.8%	−34.9%

Table 18
Average preprocessed corn stover transported from preprocessing center to bio-refinery plants in the pathway 2 supply chain (kilo-tons).

	Biorefinery code #							Biorefinery code #					
	1	2	3	4	5	6		1	2	3	4	5	6
County Code #							County Code #						
1					49.9		33			13.5			
2		49.9					34			35.1			14.8
3					49.9		35			49.9			
4					49.9		36			49.9			
5					49.9		37						49.9
6					49.9		38						49.9
7		49.9					39			49.9			
8		49.9					40						49.9
9					46.4	3.4	41				49.9		
10					49.9		42				49.9		
11	49.9						43				49.9		
12						49.9	44				49.9		
13						49.9	45				49.9		
14						49.9	46				49.9		
15	49.9						47				34.8		
16	49.9						48				49.9		
17	49.9						49				49.9		
18	49.9						50			16.3			
19	49.9						51					49.9	
20	48.2			1.6			52			4.1			
21	49.9						53						49.9
22	49.9						54			49.9			
23					49.9		55			49.9			
24						49.9	56			3			
25						49.9	57			5.4			
26						49.9	58			49.9			
27						49.9	59				49.9		
28						49.9	60						
29	37					12.9	61						
30			49.9				62						
31			49.8				63				40.9		2
32			49.9										

sources the preprocessed biomass from seventeen preprocessing centers.

5.1.3. Pathway 2 supply chain (conventional depot)

The maximum capacity of a preprocessing center in the pathway 2 supply chain is set to be 52,500 tons/year, considering the fact that the center does not need to process biomass for animal feed as it does in pathway 1 (where the capacity is 70,000 tons/year). Equal weights for both objectives are used (i.e., w_1 and w_2 were set as 0.5) along with the other relevant parameters to run the mixed integer linear program to solve the pathway 2 supply chain problem. Five hundred replications were run with different prices and supplies of corn stover from different farms. Sixty counties were selected for building preprocessing centers with respective average capacities over all the replications as shown in Table 15. Similar to the pathway 1 supply chain (see Table 12), the results in terms of the county selection and the capacity are fairly consistent across all the replications.

The resultant cost and emission are shown in Table 16.

The details of the financial performance of a typical preprocessing center in Henry County (County code 24) with an annual capacity of 52,500 tons are provided in Table 17.

As can be seen in Table 18, similar to the results shown in Table 13, the transportation cost is much less than the processing cost and the raw material cost. The detailed average transportation amounts (in kilotons) and the corresponding transportation pattern between the farms and the preprocessing center are illustrated in Fig. 5.

The average transportation amounts in kilo-tons between the preprocessing centers and the bio-refinery plants are illustrated in Table 18. Similar to the insights from Table 14, most of the preprocessing centers serve a single bio-refinery plant or at most two bio-refinery plants, depending on the capacity, geographical proximity, and the demand at the bio-refinery plant. The bio-refinery plant with the lowest production capacity (bio-refinery plant 2, 20 million gallons per year) sources the preprocessed biomass from three preprocessing centers. The bio-refinery plant with the highest production capacity (bio-refinery plant 6, 60 million gallons per year) sources the preprocessed biomass from sixteen preprocessing centers.

5.1.4. Centralized AFEX supply chain

In this model, equal weights for both objectives are used (i.e., w_1 and w_2 are set as 0.5) along with the other relevant parameters to run the mixed integer linear program to solve the proposed centralized AFEX supply chain problem. 500 replications with different prices and supplies of corn stover in various farms were experimented. The average resultant cost and emission are shown in Table 19.

The average preprocessed corn stover transportation between the farms and the bio-refinery plants across all the replications is illustrated in Table 20. All the bio-refinery plants source the corn stover from their own county or neighboring counties depending on the capacity of bio-refinery, farm capacity, geographical proximity, and price of corn stover. For example, the bio-refinery plant situated in Buchanan County (bio-refinery code 5, 50 million gallons per year) sources the corn stover from the neighboring counties of Andrew (County code 1), Clay (County code 4), Clinton (County code 5), and Holt (County code 7). The bio-refinery plant with the lowest production capacity (bio-refinery plant 2, 20 million gallons per year) sources the corn stover from a single county. The bio-refinery plant with the highest production capacity (bio-refinery plant 6, 60 million gallons per year) sources the corn stover from five counties.

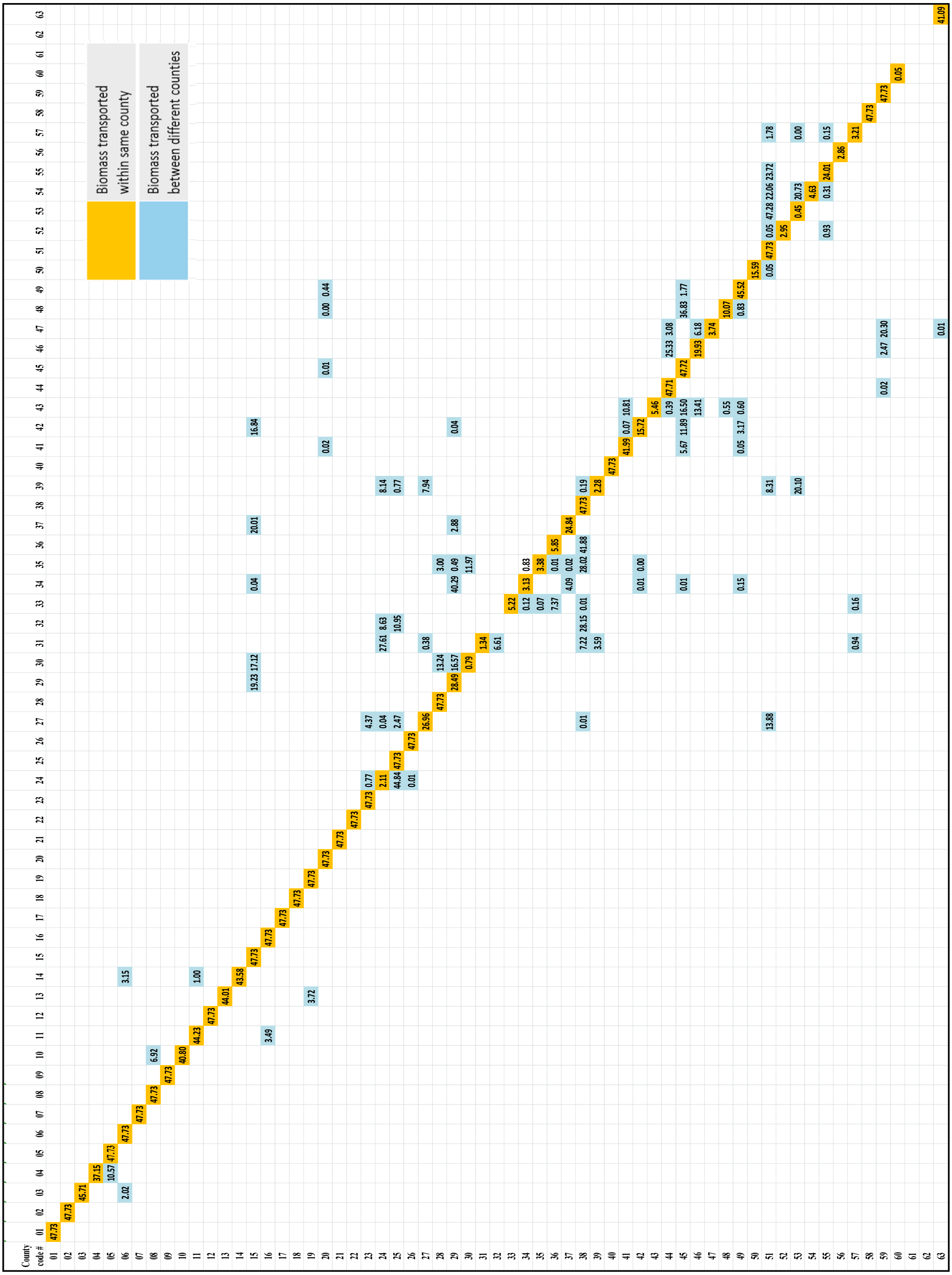


Fig. 5. Average corn stover transportation amount from farms to preprocessing centers in kilo-tons in the pathway 2 supply chain.

Table 19
Performance of the centralized AFEX supply chain.

Centralized supply chain model	Total cost ($)	Total emission (lbs. of CO_2)	Total production of the supply chain (gal)	Cost per unit production ($)	Emission per unit production (lbs. of CO_2/gal)
Mean	439,390,173	6,085,729,801	262,531,000	1.67	23.18
Half width of 95% CI	284,036	315,027	–	0.001	0.0002
Reduction compared to corn-based supply chain	27.2%	−24.2%	–	27.4%	−24.4%

Table 20
Average preprocessed corn stover transportation from farms to bio-refinery plants in the centralized AFEX supply chain (kilo-tons).

	Biorefinery code #							Biorefinery code #					
	1	2	3	4	5	6		1	2	3	4	5	6
County Code #							County Code #						
1					152.9		33						
2		210.5					34						
3						49.7	35						
4					1.6		36						
5					123.3		37						
6							38			79.5			
7					248.6		39						
8							40			445			2.2
9						120.3	41						
10							42						
11	45.8						43						
12						229.4	44						
13	46.2						45						
14							46						
15				276.7			47						
16	65.6						48						
17							49						
18							50						
19	170.4						51						
20				186.7			52						
21							53						
22	156.3						54						
23							55						
24							56						
25							57						
26			1.7			96.1	58						
27							59						
28							60						
29				55.4			61						
30							62						
31							63						
32													

5.2. Sensitivity analysis

5.2.1. Pathway 1 supply chain (quality depot)

Sensitivity analysis is conducted to examine the variations of the performance of the pathway 1 supply chain model due to the variations of different input factors. The mean values of the price and supply of corn stover over all the replications are used along with the variations of the specified interested parameters in sensitivity analysis. The performance variations due to varying the weights assigned to two objectives are illustrated in Table 21. It can be observed that the cost decreases and emission increases as the problem starts to weight cost more than emissions. The total number of nodes selected remains fairly constant. The cost per unit of bioethanol produced and the emissions per unit of bioethanol produced also remain fairly constant.

The performance variations due to varying the percentage of preprocessed biomass sold as animal feed (δ_j^s) are illustrated in Table 22. It can be seen that both overall and unit cost and emission increase with an increase in δ_j^s, the number of nodes selected for building

Table 21
Performance of the pathway 1 supply chain with different weight combinations.

Cost weight	Emission weight	Total number of pre-processing sites selected	Total cost ($)	Total emission (lbs. of CO_2)	Total production of the supply chain (gal)	Cost per unit production ($)	Emission per unit production (lbs. of CO_2 /gal)
0.1	0.9	56	544,172,595	6,852,798,321	262,531,000	2.07	26.10
0.25	0.75	56	543,748,816	6,852,926,919	262,531,000	2.07	26.10
0.5	0.5	56	543,546,385	6,853,063,940	262,531,000	2.07	26.10
0.75	0.25	56	543,370,113	6,853,488,187	262,531,000	2.07	26.11
0.9	0.1	56	542,437,382	6,856,566,572	262,531,000	2.07	26.12

Table 22
Performance of the pathway 1 supply chain with different percentages of preprocessed biomass sold as animal feed.

δ_j^s	Total number of pre-processing sites selected	Total cost ($)	Total emission (lbs. of CO_2)	Combined secondary income at the preprocessing centers from animal feed ($)	Total production of the supply chain (gal)	Cost per unit production ($)	Emission per unit production (lbs. of CO_2 /gal)
15%	49	541,071,910	6,693,707,892	75,811,091	262,531,000	2.06	25.50
20%	52	541,385,779	6,767,647,626	107,399,045	262,531,000	2.06	25.78
25%	56	543,546,385	6,853,063,940	143,198,727	262,531,000	2.07	26.10
30%	60	546,082,802	6,957,665,047	184,112,649	262,531,000	2.08	26.50

Table 23
Performance of the pathway 1 supply chain with different prices of secondary product of animal feed and percentages of preprocessed biomass sold as animal feed.

F_j	δ_j^s	Total number of preprocessing sites selected	Total cost ($)	Total emission (lbs. of CO_2)	Combined secondary income at the preprocessing centers from animal feed ($)	Total production (gal)	Cost per unit production ($)	Emission per unit production (lbs. of CO_2 /gal)
180	30%	60	545,911,217	6,952,526,555	193,802,789	262,531,000	2.08	26.48
180	20%	54	538,546,724	6,765,124,860	113,057,627	262,531,000	2.05	25.77
160	30%	Infeasible						
160	20%	52	546,486,335	6,779,190,846	100,490,335	262,531,000	2.08	25.82

preprocessing centers also increases with an increase in δ_j^s. When δ_j^s goes up, more biomass is required and hence the model starts opening up more nodes to meet this demand. Each new node incurs a new setup cost and hence the cost goes up. Meanwhile, additional processing and transportation are incurred, and hence the emission goes up, too. The overall performance of the supply chain is fairly sensitive to the variation of δ_j^s. Therefore, the variation, especially the increase of δ_j^s should be considered cautiously by practitioners, although such an increase can lead to a higher income for the preprocessing center.

The performance variations due to the combined variations of both selling price of secondary product of animal feed (F_j) and δ_j^s are shown in Table 23. As can be observed, fluctuation in F_j influences the design of the supply chain in terms of the number of nodes, and has an influence on the total cost and the total emission of the supply chain. It also affects the combined revenue generated by selling the secondary product of animal feed for the preprocessing centers. The δ_j^s, has a very pronounced effect on the design of the supply chain and its performance, as discussed above. A combination of a lower selling price ($160 per ton) for the secondary product and a higher production volume (30%) may decrease the revenue of some of the preprocessing centers and the constraint of a positive NPV (see constraint (12)) cannot be met.

The performance variations due to varying the selling price of chemically and physically pretreated biomass by the preprocessing centers to the bio-refinery plants are as shown in Table 24. As can be observed, the decrease in this price leads to an infeasibility due to the violation of the net present value constraint. The increase in this price causes a slight modification in the design of the supply chain in terms of the number of preprocessing centers intended to be built. The overall cost of the supply chain and the cost of unit production increase with an increase in this selling price as expected. Meanwhile, there is a slight decrease in the overall emission of the supply chain with an increase in this selling price, and thus the emission of unit production stays constant. The economic performance is more sensitive to the variation of the selling price of the preprocessed biomass than the environmental performance.

The performance variations due to varying the inventory level at the bio-refinery plants are shown in Table 25. As can be observed, there exist variations in total cost and total emissions, while the unit cost and the unit emission are not very sensitive to the variation in inventory level.

5.2.2. Pathway 2 supply chain (conventional depot)

Sensitivity analysis is conducted to examine the variation of the performance of the pathway 2 supply chain due to the variations of different input factors. The performance variations due to varying the weights assigned to two objectives are illustrated in Table 26. Similar to pathway 1, it can be observed that the cost decreases and emission increases as the problem starts to weight cost more than emission. While the unit cost, unit emission, and the total number of nodes selected for building preprocessing center remain fairly constant.

The performance variations due to varying the selling price of physically pretreated biomass by the preprocessing centers to the bio-refinery plants are shown in Table 27. As can be observed, the reduction of this selling price leads to infeasibility due to the violation of the net present value constraint (see constraint A(12)). The number of preprocessing centers intended to be built decreases with an increase of selling price. The overall cost of the supply chain increases due to an increase in the raw material cost. The emissions of the supply chain decrease as the model reduces one preprocessing center and this causes a corresponding decrease in transportation emission.

The performance variations due to varying the inventory level of the bio-refinery plants are shown in Table 28. Similar to the observation from Table 25, although there exist variations in total cost and total emissions, the unit cost and the unit emission do not vary with the variation of inventory.

5.2.3. Centralized AFEX supply chain

Sensitivity analysis is conducted to examine the variations in the performance of the centralized AFEX supply chain model due to the variation of different weights assigned to two objectives as illustrated in Table 29. It can be observed that the model is fairly insensitive to the variation of the weights.

5.3. Comparison among three models in two strategies

The overall performance comparison among the three models is shown in Table 30. As can be seen, all three models are better than the corn sourced supply chain in terms of cost, but worse with respect to emissions. The centralized strategy can reduce the unit production cost by 27.39%, while increasing the emissions by 24.42% compared to the corn sourced supply chain. It is better than the two models using a distributed strategy in terms of both cost and emissions. Between the two models using distributed strategies, pathway 1 outperforms pathway 2 in terms of unit cost. While, pathway 2 is superior to pathway 1 in terms of unit emission.

The decomposition of the cost incurred in producing bioethanol in bio-refinery plants is given in Table 31 for the three models under two

Table 24
Performance of the pathway 1 supply chain with different prices of chemically and physically preprocessed biomass sold to the bio-refinery plants.

Preprocessed corn stover selling price ($/ton)	Total number of pre-processing sites selected	Total cost ($)	Total emission (lbs. of CO_2)	Total production of the supply chain (gal)	Cost per unit production ($)	Emission per unit production (lbs. of CO_2 /gal)
165	Infeasible					
175	56	543,546,385	6,853,063,940	262,531,000	2.07	26.10
185	57	579,947,523	6,851,262,280	262,531,000	2.21	26.10

strategies. The biomass purchase cost with pathway 1 is much higher than pathway 2 and centralized AFEX models. This difference is mainly due to additional processes (both chemical pretreatment and physical densification) that are imposed on the corn stover purchased by bio-refinery plants with pathway 1. The reductions of purchase cost with pathway 2 and centralized AFEX models are largely offset by the increase of the operating cost compared to pathway 1. In pathway 1, the feedstock purchase cost of bio-refinery largely covers the processing cost for chemical pretreatment and physical densification, and thus, the operating cost in bio-refinery plants is much lower than the remaining two models.

Through Table 31, it can be seen that the superiority with respect to cost effectiveness of the centralized strategy in the case of Missouri is mainly attributed to a much lower transportation cost compared to the two models using a distributed strategy. This is mainly due to a lower biomass collection distance in the centralized AFEX strategy. The existing bio-refinery plants in Missouri are built in the areas with large amounts of biomass supply. While with the two models using a distributed strategy, due to the capacity limitation of the preprocessing center with the current technology, most of the counties will need to build a preprocessing center to satisfy the final demand (if we assume “one center in one county” when formulating the model), thus, the bio-refinery plant requires to source preprocessed corn stover from most of those centers. Therefore the transportation cost incurred to bio-refinery plants under the distributed strategy is much higher than the centralized one in this case.

The decomposition of the emissions incurred when using corn stover for producing bioethanol is demonstrated in Table 32 for the three models under two strategies. It can be seen that the major source of emissions is the main production processes for second generation biofuel manufacturing including AFEX, physical densification, and bioconversion (i.e., hydrolysis and fermentation). The centralized AFEX supply chain can lead to lowest emissions due to nonstop transportation along shorter distances between farms and bio-refinery plants, in comparison to the two pathways in distributed strategy. The process emissions in centralized AFEX supply chain are lower than the two pathways when distributed strategy is used because physical densification is not needed. Emissions of the pathway 1 supply chain are higher than the pathway 2 supply chain because more stover is handled in the pathway 1 supply chain for providing the animal feed. The production of animal feed in the pathway 1 supply chain can generate additional income and thus reduce the overall operation cost while increasing emissions.

To further examine the influence of the capacity limitation of the preprocessing center, we run additional sensitivity experiments that vary the capacity bound of the preprocessing center with a proportionally augmented fixed investment cost in a distributed supply chain model to approximately examine the performance when multiple preprocessing centers can be built in one county. The results are shown in Tables 33 and 34.

When allowing multiple preprocessing centers to be built in a county (i.e., the capacity is doubled or tripled as shown in Tables 33 and 34), the transportation cost of bio-refinery plants can be reduced along with a relatively small variation of the setup cost of preprocessing centers (since the number of centers intended to be built decreases proportional to the increase of the capacity bound) for both pathways. A closer look further reveals that the cost per unit of bioethanol production can be significantly reduced when doubling the centers’ capacity bound, while it is not very obvious when the capacity bound increases from 200% to 300%. Although the bio-refinery transportation cost can be further reduced when the capacity bound increases from 200% to 300%, the reduction percentage is much less than the one when the capacity bound is doubled from current bound to 200%. Also it should be noted that such an increase in capacity bound does not lead to a more competitive unit cost compared to the centralized AFEX supply chain in this case. While for the unit emission, the variations are

Table 25
Performance of the pathway 1 supply chain with different raw material inventory levels at bio-refinery plants.

Inventory holding level	Total cost ($)	Total emission (lbs. of CO_2 /gal)	Total preprocessing center sites selected	Cost per unit production ($)	Emission per unit production (lbs. of CO_2 /gal)
Weekly inventory	543,546,385	6,853,063,940	56	2.07	26.10
Monthly inventory	546,312,720	6,852,809,078	56	2.08	26.10

Table 26
Performance of the pathway 2 supply chain with different weight combinations.

Cost Weight	Emission Weight	Total number of pre-processing sites selected	Total cost ($)	Total emission (lbs. of CO_2)	Total production of the supply chain (gal)	Cost per unit production ($)	Emission per unit production (lbs. of CO_2/gal)
0.1	0.9	61	558,561,396	6,602,931,203	262,531,000	2.13	25.15
0.25	0.75	60	557,205,303	6,603,723,306	262,531,000	2.12	25.15
0.5	0.5	60	556,856,659	6,603,928,051	262,531,000	2.12	25.16
0.75	0.25	60	555,494,781	6,606,437,152	262,531,000	2.12	25.16
0.9	0.1	60	555,494,781	6,606,438,105	262,531,000	2.12	25.16

not that obvious compared to the unit cost. In pathway 1, the capacity bound increase leads to a decrease of the unit emission. In pathway 2, no obvious variation trend of the unit emission can be identified with the increase of the capacity bound.

6. Discussion

6.1. Research implications

This paper is expected to fill, to some extent, the gap of a systematic performance comparison between first and second generation biofuel supply chains. It provides a modeling tool to enhance the optimal use of bioenergy sources considering economic viability and environmental sustainability towards a green energy system. Both overall performance of the entire supply chain and interests of individual participators in the supply chain are considered. It is expected to serve the readers (including academic peers, policy makers, government agencies, business owners, etc.) who are interested in further enhancing the transition from traditional fossil fuels to renewable biofuels.

The results of the case study allow us to obtain insights into how the economic and environmental concerns vary when restructuring the supply chain infrastructure for switching first generation to second generation biofuel manufacturing. Using the state of Missouri as a case, the environmental performance in terms of GHG emissions is worse. This is mainly due to additional preprocessing operations to handle cellulosic biomass. It implies that further research focusing on the methods that can effectively reduce the GHG emissions in preprocessing is urgently needed to facilitate the wide adoption of second generation biofuel manufacturing technology.

As for the economic performance, all three models from two strategies for corn stover-sourced supply chain outperform the existing corn-sourced supply chain. This is mainly due to the cost savings from the use of cellulosic biomass instead of corn grains, which can cover the additional cost for preprocessing. Specifically, the centralized strategy is superior to the distributed one due to the fact that the existing bio-refinery plants in Missouri are located in the areas with abundant biomass supply. Their production capacities are not high enough to exhaust the supply in surrounding areas with a short collection distance. This matches the observations from the literature in terms of the threshold conditions of handling capacity and biomass collection distance to determine the superiority between centralized and distributed strategies [24]. It also implies the significance of considering the existing infrastructure of the supply chain when implementing the switch from first generation to second generation biofuel manufacturing. The option of a centralized strategy should not be excluded when the existing bio-refinery infrastructure has been built with an appropriate handling capacity in the area with a high amount of corn production. The physical densification for the corn stover may not be needed if the collection distance can be short enough so that the negative impact due to a lower density of corn stover in transportation can be offset.

Also, the increase of the capacity of proposed preprocessing centers seems to be an effective path to improve the competitiveness of the distributed supply chain. The number of such centers intended to be built can be reduced, with more preferable location selections, considering the existing bio-refinery plants to reduce the transportation cost.

6.2. Study limitations

Many assumptions have been made to simplify the proposed model in this paper, which leaves many open research issues that invite deeper investigations in the future.

6.2.1. Inclusion of harvesting system

The harvesting system is not included in the scope of this paper, which may incur an inaccurate estimation from both economic and environmental perspectives. In the United States, it is reported in the literature that currently corn stover is harvested using three-pass systems [98]. In three-pass systems, corn grain is harvested in the first pass, followed by windrowing corn stover in the second pass, and finally corn stover is baled in the third pass [98].

The selling price of corn stover for biofuel manufacturing used in this paper is estimated considering corn stover collection and storage cost when using existing three-pass harvesting systems for second generation biofuel manufacturing [25,71]. We set the constraint that no more than 60% of corn stover can be removed from the farms, so that no additional cost for additional fertilizer will be incurred considering possible soil degradation [55,61]. Therefore, most of the costs due to harvesting have been largely considered in the models with the existing harvesting system.

The emissions due to the additional fertilizers can be ignored due to the constraint of no more than 60% corn stover removal. The emissions from the fuel use during harvesting depend largely on the equipment used and time required. Specifically, compared to first generation biofuel manufacturing where corn grain needs to be collected, the time spent and fuel consumed from the operations of stover windrowing and baling need to be quantified in future research to estimate additional emissions from stover collection.

The existing three-pass harvesting systems typically are corn grain prioritized since the farmers gain most of their profit from selling the corn grain. If they harvest both corn grain and corn stover in a single pass, it may delay the grain harvest which may result in a potential

Table 27
Performance of the pathway 2 supply chain with different prices of physically preprocessed biomass sold to the bio-refinery plants.

Preprocessed corn stover selling price ($/ton)	Total number of preprocessing sites selected	Total cost ($)	Total emission (lbs. of CO_2)	Total production of the supply chain (gal)	Cost per unit production ($)	Emission per unit production (lbs. of CO_2/gal)
85	Infeasible					
95	60	556,856,659	6,603,928,051	262,531,000	2.12	25.16
105	59	583,470,359	6,603,857,325	262,531,000	2.12	25.15

business loss. When the production of cellulosic ethanol is commercialized on a large scale, there will be a constant demand for corn stover from the bio-refinery plants. Thus, it is reasonable to foresee that farmers will be interested in harvesting both corn and corn stover with a fewer pass harvesting system (e.g., a two-pass or a one-pass system) with less fuel consumption and harvesting time, since both grain and stover have the opportunity to bring in profits. Two-pass harvesting system refers to simultaneously harvesting grain and windrowing stover in the first pass, followed by the baling of stover in the second pass. In one-pass systems, both grain and stover are harvested in a single pass [98].

Generally, a one-pass system takes less time to complete the collection of both corn and corn stover compared to a two-pass system [98]. However, it requires investment for new equipment, while most of the equipment in a one-pass system is still in prototype stage since one-pass systems are not in full-fledged commercial use [99]. In addition, the selection of chopping or baling for storing the collected stover will lead to different cost superiorities between one-pass and two-pass systems [100]. Thus, the advantage in terms of cost effectiveness between one-pass and two-pass systems is not clear. Furthermore, both one-pass and two-pass harvesting systems, especially the one-pass system, will reduce the field drying time and moisture of stover may increase [101]. This will lead to additional transportation cost and dry matter loss, which influences stover cost. The possible influence on supply chain performance of this cost variation due to increased moisture is additionally discussed in “Stover Moisture.”

From an environmental perspective, there exist performance variations between various harvesting techniques. One-pass systems generally have the least collection time; however, the new equipment required in one-pass systems may have a higher power rating, and thus the advantage in terms of fuel consumption is not clear compared to multi-pass systems. Further, the use of different baling/chopping strategies will lead to different emissions’ superiorities [100]. The two-pass system is considered more feasible for the stover collection in second generation biofuel manufacturing [98]. Some research focusing on different baling/chopping strategies in two-pass systems has been reported. For example, the two-pass bale system has fuel use comparable to conventional three-pass bale systems, while the two-pass chop system uses around 50% more fuel [100].

It seems that for the existing harvesting systems, the research focusing on environmental issues is lagging behind the research focusing on economic concerns. Therefore, the emissions due to the harvesting operations have been left out of the scope of this paper considering the existing harvesting system. While for the harvesting system with fewer passes that may be possibly adopted to accommodate the large scale cellulosic biofuel production in the future, both cost and emission studies are not completed. More investigation on the variations of cost and emission is needed to validate the possible options of harvesting system switch.

6.2.2. Uncertainty modeling

The uncertainties in the supply chain modeling consist of the concerns from various aspects such as supply, demand, facility operation performance, and some other external influencing factors. In this research, the uncertainty of the performance of the facilities involved in the supply chain (e.g., equipment degradation) is not considered when evaluating the lifetime performance. The demand uncertainty is not considered, either. The existing literature has indicated that the demand for stover stays practically fixed by the capacity of bio-refinery plants in the given region [102]. The supply uncertainty due to non-constant participation willingness of farmers when offering corn stover to the biofuel supply chain is examined using stochastic analysis with varied inputs of corn stover supply and corn stover price. The complex relationships among the supply, selling price, and other external economic factors such as gas price are simplified through separately extracting the price and supply amount from the respective distributions

Table 28
Performance of the pathway 2 supply chain with different raw material inventory levels at bio-refinery plants.

Inventory holding level	Total cost ($)	Total emission (lbs. of CO_2/gal)	Total preprocessing center sites selected	Cost per unit production ($)	Emission per unit production (lbs. of CO_2/gal)
Weekly inventory	556,856,659	6,603,928,051	60	2.12	25.16
Monthly inventory	559,547,764	6,603,658,999	60	2.13	25.15

Table 29
Performance of the centralized AFEX supply chain with different weight combinations.

Cost weight	Emission weight	Total number of farms selected	Total cost ($)	Total emission (lbs. of CO_2)	Total production of the supply chain (gal)	Cost per unit production ($)	Emission per unit production (lbs. of CO_2/gal)
0.1	0.9	18	439,290,902	6,085,418,465	262,531,000	1.67	23.18
0.25	0.75	18	438,721,583	6,085,426,788	262,531,000	1.67	23.18
0.5	0.5	18	438,721,583	6,085,426,974	262,531,000	1.67	23.18
0.75	0.25	18	438,721,583	6,085,427,353	262,531,000	1.67	23.18
0.9	0.1	18	438,721,583	6,085,427,233	262,531,000	1.67	23.18

Table 30
Performance comparison.

Supply chain	Total cost ($)	Total emission (lbs. of CO_2)	Total bioethanol production (gal)	Cost per unit production ($/gal)	Emission per unit production (lbs. of CO_2/gal)
Corn sourced (baseline) mean	603,567,475	4,891,616,936	262,531,000	2.30	18.63
Half width of 95% CI	508,281	204,338	–	0.002	0.001
Pathway 1 supply chain mean	543,852,062	6,853,317,839	262,531,000	2.07	26.10
Half width of 95% CI	258,203	345,213	–	0.001	0.00034
Pathway 2 supply chain mean	556,882,330	6,604,038,135	262,531,000	2.12	25.16
Half width of 95% CI	302,236	428,362	–	0.004	0.0002
Centralized AFEX supply chain mean	439,390,173	6,085,729,801	262,531,000	1.67	23.18
Half width of 95% CI	284,036	315,027	–	0.001	0.0002

Table 31
Cost decomposition in bio-refinery plants for three corn stover-sourced supply chain models.

Supply chain model	Total cost ($)	Transportation cost ($)	Feedstock purchase cost ($)	Inventory cost ($)	Annualized cost of AFEX ($)	Operating cost ($)
Pathway 1 supply chain	543,852,062	33,724,219	450,719,690	862,291	–	58,545,861
Pathway 2 supply chain	556,882,330	32,190,956	257,554,111	907,675	7,973,559	237,888,594
Centralized AFEX supply chain	439,390,173	9,099,259	162,784,329	–	8,068,439	237,888,594

Table 32
Decomposition of emissions in the corn stover supply chain.

	Transportation emissions (CO_2 lbs)	Total process emissions (CO_2 lbs)	AFEX emissions (CO_2 lbs)	Densification emissions (CO_2 lbs)	Bioconversion emissions (CO_2 lbs)
Pathway 1 supply chain	91,760,637	6,762,843,137	1,203,239,537	434,620,699	5,124,982,902
Pathway 2 supply chain	78,723,958	6,525,517,361	943,038,987	457,495,472	5,124,982,902
Centralized AFEX supply chain	17,707,912	6,068,021,889	943,038,987	–	5,124,982,902

built using the recent historical records of Missouri, while the possible correlation between price and supply is not considered.

The results from the case study offer 95% confidence intervals for the unit cost and unit emission with a fairly narrow width, which shows the performance on unit production is not very sensitive to the variations of the price and supply modeled in this paper. This is mainly due to (1) not all sources of uncertainty being considered in the analysis, and (2) the raw data used for modeling the variation of price and supply are from a local area (i.e., Missouri) in recent years (the past four to five years) with less fluctuation.

Future research considering more uncertain factors and using more historical data for a broader area should be implemented to strengthen the robustness of the model. A mathematical model that can quantitatively reveal the relationships between different input factors with uncertainties needs to be derived. In addition, the issue of corn demand "post-replacement by corn stover" should also be studied. Since a large amount of corn is especially planted and used for biofuel production rather than food, a new target customer group for selling these "replaced corn" needs to be carefully investigated. The selling outlets of the replaced corn and the corresponding price could influence the willingness of the farmers to offer corn stover for biofuel manufacturing, especially in the areas with a mature system of first generation biofuel manufacturing and supply.

6.2.3. *Conflicts between different participants*

In the model presented in this paper, the overall performance of the supply chain is optimized while considering the interests from different individual participants in the supply chain. Corresponding constraints

Table 33
Sensitivity analysis for preprocessing capacity bounds for the pathway 1 supply chain.

Supply chain	Total setup cost of the preprocessing centers ($)	Total transportation cost of bio-refinery ($)	Total preprocessing center built	Cost per unit production ($)	Emission per unit production (lbs. of CO_2 /gal)
Current capacity bound (Mean)	432,715,421	33,724,219	56	2.07	26.10
200% capacity bound (Mean)	461,792,546	11,491,052	30	2.02	25.89
300% capacity bound (Mean)	468,410,242	9,079,779	21	2.02	25.86

Table 34
Sensitivity analysis for preprocessing capacity bounds for the pathway 2 supply chain.

Supply chain	Total setup cost of the preprocessing centers ($)	Total transportation cost of bio-refinery ($)	Total preprocessing center built	Cost per unit production ($)	Emission per unit production (lbs. of CO_2 /gal)
Current capacity bound (Mean)	63,202,475	32,190,956	59	2.12	25.15
200% capacity bound (Mean)	61,207,475	11,797,092	33	2.04	24.96
300% capacity bound (Mean)	61,645,500	2,238,448	23	2.03	25.02

Table 35
Emission comparison when redundant stover handling is considered.

Supply chain	Emissions of the supply chain (not including redundant stover handling) (lbs. of CO_2)	Corn stover used for biofuel production	Corn stover burned (tons)	Emissions due to burning of corn stover (lbs. of CO_2)	Total emissions (supply chain plus redundant stover handling) (lbs. of CO_2)	Total bioethanol production (gal)	Total unit emission (lbs. of CO_2/gal)	Reduction
Corn sourced	4,891,616,936	0	5,794,256	28,102,141,600	32,993,758,536	262,531,000	125.68	–
Pathway 1	6,853,317,839	3,957,729	1,836,527	8,907,155,950	15,760,473,789	262,531,000	60.03	52%
Pathway 2	6,604,038,135	2,908,931	2,885,325	13,993,826,250	20,597,864,385	262,531,000	78.46	38%
Centralized AFEX	6,085,729,801	2,763,484	3,030,772	14,699,244,200	20,784,974,001	262,531,000	79.17	37%

Table 36
Performance of the pathway 1 supply chain with different stover purchase prices.

Corn stover price ($/ton)	Unit cost ($/gal)	Unit emission (lbs. of CO_2 /gal)	Selling price of preprocessed corn stover ($/ton)	Selling price of animal feed ($/ton)	Total revenue ($)	Total raw material cost ($)	Transportation cost ($)	Processing cost ($)	Total profit ($)
60	2.07	26.10	175	171	555,548,412	204,739,332	7,930,434	311,888,256	30,990,390
80	2.28	26.10	191.5	194	623,708,023	273,284,318	7,930,434	311,888,256	30,605,015
100	2.48	26.10	212	218	692,491,145	341,829,305	7,930,434	311,888,256	30,843,150

Table 37
Performance of the pathway 2 supply chain with different stover purchase prices.

Corn stover price ($/ton)	Unit cost ($/gal)	Unit emission (lbs. of CO_2 /gal)	Selling price of preprocessed corn stover ($/ton)	Total revenue ($)	Total raw material cost ($)	Transportation cost ($)	Processing cost ($)	Total profit ($)
60	2.12	25.16	95	262,531,000	158,122,216	5,260,955	78,805,578	20,342,251
80	2.32	25.16	114.2	315,589,897	211,011,866	5,260,955	78,805,578	20,511,498
100	2.52	25.16	133.3	368,372,445	263,901,516	5,260,955	78,805,578	20,404,396

Table 38
Performance of the centralized AFEX supply chain with different stover purchase prices.

Corn stover price ($/ton)	Unit cost ($/gal)	Unit emission (lbs. of CO_2 /gal)
60	1.67	23.18
80	1.88	23.18
100	2.09	23.18

(e.g., the NPV constraint for the preprocessing center) are used in the formulation, which may reduce the number of feasible solutions for the problem. The interests from different parties in the supply chain may have mutual conflicts. For example, the motivation of bio-refinery plants in the supply chain is largely represented by a more cost effective alternative feedstock of corn stover instead of corn. The interests of the preprocessing centers are preserved by a larger amount of income when selling the preprocessed feedstock to bio-refinery plants.

Different constraint relaxation options can be experimented in future research to examine and compare the overall benefits to the entire supply chain and the possible gains and losses to different individual participants. The policy of overall benefit allocation and cross subsidization can be further explored.

6.2.4. Redundant corn stover handling

The redundant corn stover is typically burned [103]. In the United States, around 6% of the corn stover is used for livestock and other industries [104], and around 40% of the corn stover is required to maintain the organic carbon levels of soil [56]. This means that approximately 54% of the corn stover may be burned in open fields. When the feedstock for bioethanol production is switched from corn to corn stover, more corn stover will be consumed and the amount of burning could be reduced. It is estimated that 4850 lbs of CO_2 emission is incurred by burning one ton of corn stover [105]. If this redundant corn stover handling is considered, the comparison of unit emission between the three proposed supply chains and the corn-sourced supply chain is as illustrated in Table 35. The unit emission of corn-sourced supply chain is much higher than the result when redundant stover handling is not considered. It can be seen that a reduction of 52%, 38%, and 37% can be achieved in the unit emission by the pathway 1, pathway 2, and centralized AFEX supply chains compared to the corn-sourced supply chain. The pathway 1 supply chain outperforms the pathway 2 and centralized AFEX supply chains because of the additional stover consumed for secondary product of animal feed at the preprocessing centers.

6.2.5. Stover moisture

The existing three-pass harvesting system can offer the stover in the U.S. cornbelt region with the moisture level typically around 15–20% [93]. The densification and AFEX equipment used in the depots is capable of handling this level of moisture [53]. As mentioned earlier, the harvesting systems with fewer passes will be preferred in the future to accommodate the stover collection in second generation biofuel manufacturing. One main drawback, especially for one-pass systems, is the reduced field drying time, which results in a higher moisture level. This main negative impact is worth analyzing further (i.e., increased stover cost due to the increased moisture level) although one-pass systems are not commercially available now. Therefore, a sensitivity analysis considering two higher stover price possibilities (i.e., $80 and $100 per ton) for all three supply chain models is implemented. The performance variations are shown in Tables 36–38.

Note that, in the pathway 1 and pathway 2 supply chain models, the increase in corn stover price leads to the violation of the NPV constraints for the preprocessing centers. Therefore, selling prices of preprocessed stover (in both the pathway 1 and pathway 2 supply chains) and animal feed (in the pathway 1 supply chain) are increased accordingly to cover the increase in raw material cost and to maintain a similar profit level for the preprocessing center. It can be seen that with the increase of stover purchase price due to increased moisture with the use of single-pass harvesting system, the unit emission can largely stay constant, while the unit cost is quite sensitive to this variation. In the pathway 1 supply chain, when corn stover price increases to $80 per ton, the unit cost is increased to $2.28, which is very close to the unit cost in the corn-sourced baseline model. When stover price is increased to $100 per ton, the unit cost exceeds the baseline model of the corn-sourced supply chain. A similar trend can be seen from the pathway 2 and centralized AFEX supply chain models. Specifically, the increase of the stover farmgate price leads to the pathway 2 supply chain less economically competitive compared to the corn-sourced baseline model. While the centralized AFEX model can still keep the advantage of unit cost when compared to the baseline model although a significant increase of the unit cost. It is because the centralized AFEX supply chain has a much lower unit cost with the stover farmgate price considering the existing harvesting systems compared to the two pathway supply chains under the distributed strategy.

In addition, the selection of baling or chopping for stover storage also influences moisture level and feedstock stability. Earlier research has indicated that when the chopped logistic system is used combined with a two-pass harvesting system and stover is stored in bulk format in silage bags, it could result in the lowest farmgate price of stover [98,100]. The dry matter loss associated with ensiled biomass in storage is significantly less compared to high moisture bales stored aerobically in existing three-pass systems. Additionally, such storage can reliably limit the risks of loss from fire in storage and preprocessing operations [101].

This implies that moisture issues and storage strategy, when the harvesting systems with fewer passes are used in the future, need to be well addressed. Otherwise, the cost advantage in second generation biofuel will be significantly weakened.

7. Conclusion and future work

In this paper, we propose a corn stover-sourced biofuel supply chain considering two strategies for conducting preprocessing operations to restructure the existing supply chain and offer cellulosic feedstock for bio-refinery in second generation bioethanol manufacturing. Two major performance measures (i.e., cost and emission) from economic and environmental perspectives are modeled as the optimization objective using a mixed integer linear program to select the locations for building preprocessing centers, the capacity of the preprocessing centers, and the material flows. A case study is conducted based on the state of Missouri in the United States.

The results of the case study show that all three models from two restructuring strategies investigated in the case study are more cost effective but less environmentally friendly than the first generation corn-based biofuel supply chain. Specifically, the centralized strategy outperforms the distributed one with a larger cost reduction and a lower emission increase. It reduces the unit cost by 27.39% while increasing the unit emission by 24.42% compared to the corn-sourced supply chain. On the other hand, pathway 1 and pathway 2 models under the distributed strategy can reduce the unit cost by 10% and 7.8%, while increasing the unit emission by 36.5% and 34.9%, respectively, compared to the corn-sourced supply chain. These results reveal that the major impedance to such a replacement may be from the perspective of environmental sustainability.

The first generation biofuel may lead to the destruction of wild lands and pastures to grow corn, soybean and other crops, which may have additional negative effects on the environment. Similar effects on the wild land of second generation biofuel manufacturing should be less evident since the biomass feedstocks are non-edible crop matter with high availability from existing farms. Since the scope of this paper does not include crop planting and harvesting, the emissions in such earlier biomass production stages are not included. The corn stover harvesting might have negative impacts, such as soil compaction, and increased emission, especially when a two or three pass harvesting system is used. Even for a one-pass harvesting system, the emission impact is not clear when corn stover is used on a large scale for second generation biofuel manufacturing.

For future work, the research scope can be expanded to include the harvesting and planting system so that a more accurate comparison between first and second generation biofuel supply chains can be systematically implemented, especially focusing on the economic and environmental interests of the harvesting systems with fewer passes. The complex interrelationships of the price, supply, and target customers between corn and corn stover when switching from first generation to second generation biofuel manufacturing could be further quantified. The uncertainties in terms of the operations during the lifetime should be integrated into the model when examining the model performance. The conflicts between different participants in the supply chain need to be analyzed and the overall benefit allocation should be explored. In addition, the potential risks that may affect different sections of the biofuel supply chain need to be considered and further studied to identify the resilience of given supply chain configurations. A mixed biomass source including both corn and corn stover in the supply chain can also be one interesting direction.

Appendix A. Unit cost and unit emission calculation for biofuel production using corn grain

The total bioethanol in gallons that can be produced using corn in bio-refinery plant k can be calculated by (A1).

$$TP_k^c = \sigma_k^c \sum_i B_{ik} \tag{A1}$$

Let PP_k^c be the cost per gallon of bioethanol produced at bio-refinery plant k. It can be calculated by (A2).

$$PP_k^c = C_k^c / TP_k^c \tag{A2}$$

where C_k^c is the total cost for producing bioethanol at bio-refinery plant k which includes the material purchase cost, the transportation cost, the raw material (corn) holding cost, and the operation costs of milling, hydrolysis and fermentation. It can thus be calculated by (A3).

$$\begin{aligned} C_k^c = &\textstyle\sum_i P_i^c B_{ik} + \sum_i \lceil B_{ik}/M^c \rceil D_{f_i b_k} T_{f_i b_k}^c + o^{cM} \sum_i B_{ik} \\ &+ o^{cH} \beta^{cM} \textstyle\sum_i B_{ik} + o^{cF} \beta^{cM} \beta^{cH} \sum_i B_{ik} + \frac{h^c}{50} \sum_i B_{ik} \end{aligned} \tag{A3}$$

where $\lceil\ \rceil$ is the ceiling function. We assume the bio-refinery plant keep the raw material inventory level of corn grain so that it can satisfy a one-week production requirement (assuming 50 weeks per year). Accordingly, the cost per gallon of bioethanol produced at bio-refinery plants throughout the supply chain can be calculated by (A4).

$$PP^c = \sum_k C_k^c / \sum_k TP_k^c \tag{A4}$$

Similarly, the emission per gallon of bioethanol produced at bio-refinery plants throughout the supply chain can be calculated by (5).

$$PE^c = \sum_k E_k^c / \sum_k TP_k^c \tag{A5}$$

where E_k^c is the total emission incurred by producing bioethanol using corn at bio-refinery plant k, which can be calculated by (A6). It includes the emissions incurred by corn transportation from various farms to bio-refinery plant k and corn processing through milling, hydrolysis and fermentation at bio-refinery plant k.

$$\begin{aligned} E_k^c &= \textstyle\sum_i \left[(e^0 + \alpha M^c)\cdot D_{f_i b_k} + e^0 D_{f_i b_k}\right]\cdot\lceil B_{ik}/M^c\rceil \\ &+ e^{cM}\textstyle\sum_i B_{ik} + e^{cH}\beta^{cM}\sum_i B_{ik} + e^{cF}\beta^{cM}\beta^{cH}\sum_i B_{ik} \end{aligned} \tag{A6}$$

Note that we assume that the truck used for transportation will be empty on its return trip. Also note that, the scope of this research is from the purchase and transportation of the biomass from the farms.

Appendix B. Constraints of the pathway 2 supply chain

$$PP_k^{sd2} \leqslant PP_k^c,\ \ \forall\ k \tag{A7}$$

$$\sum_j b_{f_i p_j}^{sd2} \leqslant Q_i,\ \ \forall\ i \tag{A8}$$

$$\sum_i b_{f_i p_j}^{sd2} \leqslant y_j^{sd2},\ \ \forall\ j \tag{A9}$$

$$\sum_k b_{p_j b_k}^{sd2} \leqslant \beta^{sP} y_j^{sd2},\ \ \forall\ j \tag{A10}$$

$$\sum_j b_{p_j b_k}^{sd2} \leqslant (W_k^s/\beta^{sC}),\ \ \forall\ k \tag{A11}$$

$$NPV_j^{sd2} > 0,\ \ \forall\ j \tag{A12}$$

$$b_{f_i p_j}^{sd2},\ b_{p_j b_k}^{sd2},\ y_j^{sd2} \geqslant 0 \tag{A13}$$

$$x_j^{sd2} \in \{0, 1\} \tag{A14}$$

$$b_{f_i p_j}^{sd2} \leqslant N x_j^{sd2},\ \ \forall\ i,\ \ \forall\ j \tag{A15}$$

$$b_{p_j b_k}^{sd2} \leqslant N x_j^{sd2},\ \ \forall\ j,\ \ \forall\ k \tag{A16}$$

$$y_j^{sd2} \leqslant N x_j^{sd2},\ \ \forall\ j \tag{A17}$$

$$\sum_k TP_k^{sd2} = D \tag{A18}$$

$$x_j^{sd2} \leqslant N y_j^{sd2},\ \ \forall\ j \tag{A19}$$

$$y_j^{sd2} \leqslant K_2,\ \ \forall\ j \tag{A20}$$

In (A12), NPV_j^{sd2} can be calculated by (A21).

$$NPV_j^{sd2} = -CS_j^{sd2} + \sum_{t=3}^{T+2} \frac{\text{Profit}_j^{sd2}}{(1+r)^t} \tag{A21}$$

In (A21), CS_j^{sd2} can be calculated by (A22).

$$CS_j^{sd2} = (I_j^{sd2}/3) + (2I_j^{sd2}/3(1+r)) \tag{A22}$$

where I_j^{sd2} only consists of the setup cost of physical densification system, which can be calculated by (A23).

$$I_j^{sd2} = G^P\cdot\lceil y_j^{sd2}/g^P\rceil \tag{A23}$$

In (A21), Profit_j^{sd2} can be calculated by subtracting the cost of purchasing corn stover from farms by preprocessing center j, the cost of corn stover transportation between farms and preprocessing center j, and the operational cost of preprocessing center j, from the revenue of the preprocessing center j as shown in (A24).

$$\text{Profit}_j^{sd2} = z_j^{sd2}\sum_k b_{p_j b_k}^{sd2} - \sum_i P_i^s b_{f_i p_j}^{sd2} - \sum_i \lceil b_{f_i p_j}^{sd2}/M^{su}\rceil D_{f_i p_j} T_{f_i p_j}^{su} - o^{sP}\sum_i b_{f_i p_j}^{sd2} \tag{A24}$$

Appendix C. Constraints of the centralized AFEX supply chain

$$PP_k^{sc} \leqslant PP_k^c, \ \forall \ k \tag{A25}$$

$$\sum_k b_{f_i b_k}^{sc} \leqslant Q_i, \ \forall \ i \tag{A26}$$

$$\sum_i b_{f_i b_k}^{sc} \leqslant (W_k^s/\beta^{sC}), \ \forall \ k \tag{A27}$$

$$b_{f_i b_k}^{sc} \geqslant 0 \tag{A28}$$

$$\sum_k TP_k^{sc} = D \tag{A29}$$

In (A29), TP_k^{sc} is the total bioethanol in gallons that can be produced using corn stover in bio-refinery plant k, which can be calculated by (A30).

$$TP_k^{sc} = \sigma_k^s \beta^{sC} \sum_i b_{f_i b_k}^{sc} \tag{A30}$$

In (A25), PP_k^{sc} is the cost per gallon of bioethanol produced at bio-refinery plant k. It can be calculated by (A31).

$$PP_k^{sc} = C_k^{sc}/TP_k^{sc} \tag{A31}$$

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