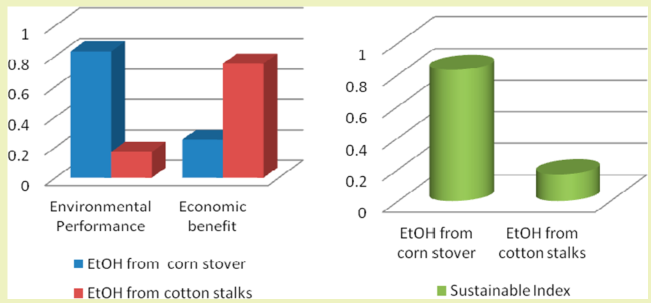
ACS Sustainable Chemistry & Engineering
Research Article
pubs.acs.org/journal/ascecg

Bioethanol Production from Cotton Stalks or Corn Stover? A Comparative Study of Their Sustainability Performance

Evangelos C. Petrou* and Costas P. Pappis

Department of Industrial Management and Technology, University of Piraeus, 80 Karaoli and Dimitriou Street, 18534, Piraeus, Greece



ABSTRACT: The production of second generation biofuels, ones produced from lignocellulosic materials, has not yet been developed in a full commercial scale. However, a considerable number of pilot and demonstration plants have been announced or set up in recent years with research activities taking place mainly in North America, Europe, and a few other countries, while commercial plants are about to start operation at the same time their environmental and economic performance are under examination. These performance issues are very sensitive on a variety of parameters such as feedstock material, production technology, logistics involved, etc. In this study, the sustainability performance of two alternative bioethanol production systems, namely, one using cotton stalks and a second using corn stover feedstock, are examined and compared using the analytic hierarchy process method. Life cycle impact assessment is used in order to evaluate each alternative's environmental performance. For this purpose, a modern, powerful, state of the art software (SimaPro) is used. The systems' economic performance is based on cost/benefit calculations.

KEYWORDS: *Bioethanol, Analytical hierarchy process, Life cycle impact assessment*

INTRODUCTION

Lignocellulosic materials, particularly agricultural residues, seem to be a very attractive source for biofuel production (second generation biofuels) as indicated in recent literature.[1−3] The reasons for this are as follows: (1) They have great potential. (2) They have no adverse effect on food production. (3) They have the least negative impacts (economic, environmental, and social) to human systems compared to energy plant cultivations.[1,4] In its latest (2014) report, the Working Group II of the Intergovernmental Panel for Climate Change concludes that options with low life cycle emissions such as biomass residues can reduce greenhouse gas (GHG) emissions.[5]

Several pilot and demonstration plants have been operated, while some full commercial plants are about to start their production.[6−9] Relevant research activities, including performance issues such as environmental and economic ones, are taking place, mainly in North America, Europe, and a few other countries, such as Brazil, China, India, etc.[10] In general, the performance of such materials when used for the production and supply of biofuels depends on a variety of parameters such as kind of feedstock material, production technology, logistics involved, etc.[1,11] The evaluation of such performance is not straightforward, particularly in cases where multiple unrelated objectives or attributes have to be taken into account in the decision-making process. In such cases, operational research methodologies have to be employed in order to arrive at safer conclusions.[12] In this study, the sustainability performance of two candidate alternative bioethanol production systems, namely, one using cotton stalks and a second using corn stover feedstock, are examined and compared using the analytic hierarchy process method. Sustainability is meant to be composed of two criteria, namely, economic and environmental ones, which have been taken into account for the final evaluation. Life cycle impact assessment and, more specifically, the Eco-Indicator 99 method is used in order to evaluate each alternative's environmental performance. For this purpose, a modern, powerful, state of the art software (SimaPro) is employed, while cost/benefit calculations are used for the evaluation of the systems' economic performance.

Corn stover ethanol production has been extensively studied with the exception of the feedstock logistics issue.[13] Conversely, ethanol production from cotton stalks started to concern researchers only recently.[14,15] These facts, in combination with the great potential of this type of biomass, gave rise to the present study. Among these two materials, which ethanol production system might exhibit higher sustainability performance? To the best of our knowledge, this is the first comparative assessment attempting to answer this question and provide real data about the alternatives' feedstock logistics.

As shown by the analysis performed and based on several assumptions and simplifications made, the corn stover ethanol production system exhibits better environmental performance than the cotton stalks ethanol system, whereas the second

Received: April 12, 2014
Revised: June 1, 2014
Published: June 26, 2014

prevails slightly in the economic perspective. Regarding the social criterion, the two options may be considered as comparable. After aggregating these performances into a unique sustainability index, corn stover ethanol seems to dominate.

METHODOLOGY

Theoretically, the metrics used for the measurement of sustainability involves the performance in certain domains, namely, environmental, social, and economic, because these are its three pillars.[16] Metrics for the social domain (e.g., poverty, equity, employment, education, skills, etc.) is difficult to quantify. Nonetheless, a brief presentation of the social impacts of a bioethanol production system using agricultural wastes as raw material is presented below.

The positive effect in unemployment reduction at local communities is the main social impact. Local subcontractors undertake the work for the agricultural residue (corn stover and cotton stalks) collection and transportation to the ethanol production units. These subcontractors are mainly farmers who undertake the work during an inactive period for them (from mid-October to mid-December). A typical subcontractor's team includes at least the personnel and the equipment listed in Table 1.

Table 1. Equipment and Personnel for Lignocellulosic Residues Collection

equipment	personnel
1 tractor + 1 cutting machine	1 operator
1 tractor + 1 baler	1 operator
1 28 t truck	1 operator

As Table 1 shows, a typical subcontractor employs at least three persons for a short period of 40−50 days when the weather conditions are suitable for biomass collection. The collection rate of such a team is about 150 t/day, which means that for the entire biomass quantity needed for the bioethanol plant a number of 100 typical subcontractors is required or 300 persons must be employed for a period of about two months. This is equal to the employment of 50 persons yearly.

Because the present study is a comparative assessment of two alternative production systems and the aforementioned social impact is the same in both alternatives examined, it is meaningless to quantify and aggregate it with the other quantified economic and environmental impacts.

In contrast to social impacts, metrics for the economic and environmental domains are easier to calculate because plenty of tools are available to do this such as material balances, stoichiometric data, and economic analysis. Also, environmental and economic performances have to be assessed for the two alternatives in order to be compared as they differentiate, at least in part. Thus, environmental and economic criteria were selected for the systems' sustainability evaluation in this study. The sustainability performance of each bioethanol production system is expressed as a performance index combining the environmental and economic criteria and is calculated using the analytic hierarchy process.[17] Cost/benefit calculations are used for the evaluation of the systems' economic performance, while the environmental performance is evaluated by the Eco-Indicator (EI 99) method. The combined performance index is then used for the selection of the best scenario from a sustainability perspective. A popular and state of the art software (SimaPro-Version 7.1) is used to determine the environmental performance of each scenario. SimaPro is a professional tool for collecting, analyzing, and monitoring the environmental performance of products and services, following the ISO 14040 series recommendations. Among the life cycle impact assessment methods used by this software, EI 99 is selected because it is used extensively in similar evaluations, and in addition, it includes the land use impact category, which is important in agricultural production systems (as in the case of cotton and corn cultivation). The 2002 National Renewable Energy Laboratory's (NREL) report, referring to the design of an ethanol production system based on corn stover biomass, was used as a standard for the description of the production systems under evaluation.[13] Also, data concerning the unit processes describing each production system were gathered by field research in Greece. Where no data was available, proper assumptions were made. The economic performance of each alternative was measured in terms of total supply chain cost, in particular, operational cost from field to distillery, as the other costs (e.g., ethanol distribution cost) are the same for both alternatives. The plant is assumed to be situated in the district of Thessaly (Greece) because it can provide either the whole biomass quantity needed (in the case of corn stover) or the most part of it (in the cotton stalks case). The selected unit basis is 1 kg EtOH (95% in water on a mass basis) at the distillery.

THE ALTERNATIVE SYSTEMS

Both alternative systems are evaluated with respect to the "field to distillery" bioethanol production, which includes the following stages: feedstock harvesting from fields; transport and feedstock storage and handling (size reduction, etc.); pretreatment and hydrolyzate conditioning process; saccharification and cofermentation process; product, solids, and water recovery stage (distillation, dehydration, evaporation and solid−liquid separation); wastewater treatment; product storage; and power cogeneration (byproduct combustion for steam and electricity generation).

Alternative System A: Ethanol Production from Corn Stover. The system is fed with corn stover harvested in Greece (Thessaly district). The biomass collection procedure includes the corn stalks cutting and baling in large cylindrical bales using tractors and balers.[18] The bales are loaded from fields to trailers hauled by tractors and are transferred to open depots near the fields, from where they are finally transported to the ethanol plant by 28 t lorry fleets. Trucks were considered to travel empty one way.

Key figures of the biomass collection system are presented in Table 2, whereas principal inventory values of the ethanol production system using this biomass are presented in Table 3.

Table 2. Key Figures of Corn Stover Collection and Transportation System

	value	note
feedstock quantity (t corn stover on a dry basis/yr)	750,000	
harvested area (ha)	125,000	
corn field biomass yield (t/ha)	5.70−7.50	
baling rate (ha/h)	1.7	10−23 bales/h
corn stover bale mass (t)	0.450	bale diameter: 1.2 m
bale density (kg/m^3)	400	
biomass moisture content (% w/w)	14	3 days after the collection
biomass acquisition cost at plant gate (€/t)	35	
average distance for feedstock transportation (km)	70	5 km by tractor + rail and 65 km by lorry 28 t

The industrial process yield in the distillery is 284.4 g/kg of dry feedstock. This value is 80% of the theoretical yield based on the chemical composition of corn stover as provided by NREL measurements (measurements refer to the United States).[13] Corn stover is composed of glucan (37.4%), xylan (21.1%), lignin (18.0%), arabinan (2.9%), galactan (2.0%), mannan (1.6%), ash (5.2%), acetate (2.9%), protein (3.1%), extractives (4.7%), and unknown soluble solids (1.1%)

Table 3. Indicative Inventory Values of Ethanol Production System Using Corn Stover

	value	note
ethanol plant capacity (t ethanol/yr)	213,300	
power cogenerated (MWh/yr)	160,000	2.28 KWh/gal EtOH according to NREL report
Corn stover input at plant (kg/kg EtOH)	3.5	on a dry basis
sulfuric acid at plant (kg/kg EtOH)	0.033	
chemicals organic at plant (kg/kg EtOH)	0.0017	
quicklime (kg/kg EtOH)	0.0244	
propane at plant (kg/kg EtOH)	0.0002	
tap water (kg/kg EtOH)	7.9	
lubricating oil at plan (kg/kg EtOH)	0.0004	
maize starch (kg/kg EtOH)	0.0133	

(composition in % w/w on a dry basis). Because similar data for Greek corn stover are not available, we assume that their composition, and thus the yield of the industrial process, is identical to those of the United States case.

Alternative System B: Ethanol Production from Cotton Stalks. The system is fed with cotton stalks harvested in Greece (Thessaly and Macedonia districts). In particular, 60% of the needed feedstock is assumed to come from Thessaly and the rest from Macedonia. The concept of the biomass collection and transportation system is similar to that of alternative A.

Key figures of the biomass collection system are presented in Table 4, whereas principal inventory values of the ethanol production system using this biomass are presented in Table 5.

Table 4. Key Figures of Cotton Stalks Collection and Transportation System

	value	note
feedstock quantity (t cotton stalks on a dry basis/yr)	750,000	
harvested area (ha)	300,000	
average distance for feedstock transportation (km)	226	16 km by tractor + rail and 210 km by lorry 28 t
cotton field biomass yield (t/ha)	1.80−2.50	
baling rate (ha/h)	1.7	10−23 bales/h
cotton stalks bale mass (t)	0.450	bale diameter: 1.2 m
bale density (kg/m^3)	220	
biomass moisture content (% w/w)	14	3 days after collection
biomass acquisition cost at plant gate (€/t)	35	

The industrial process yield in the distillery is assumed to be 80% of the theoretical yield based on cotton stalks chemical composition as in the case of corn stover ethanol production. Because chemical composition data for the Greek cotton stalks are not available, data from the literature were used.[19] Cotton stalks are composed of glucan (31.1%), xylan (8.3%), lignin (30.1%), arabinan (1.3%), galactan (1.1%), ash (6.0%), extractives (9.0%), and others (13.1%) (composition in % w/w on a dry basis). The aforementioned yield is based on the chemical composition mentioned above and is 178.7 g/kg of dry feedstock.

Table 5. Indicative Inventory Values of Ethanol Production System Using Cotton Stalks

	value	note
ethanol plant capacity (t ethanol/yr)	134,025	
power cogenerated (MWh/yr)	269,000	proportional to lignin concentration of feedstock
cotton stalks input at plant (kg/kg EtOH)	5.9	on a dry basis
sulfuric acid at plant (kg/kg EtOH)	0.033	
chemicals organic at plant (kg/kg EtOH)	0.0017	
quicklime (kg/kg EtOH)	0.0244	
propane at plant (kg/kg EtOH)	0.0002	
tap water (kg/kg EtOH)	7.9	
lubricating oil at plan (kg/kg EtOH)	0.0004	
maize starch (kg/kg EtOH)	0.0133	

RESULTS

Environmental Performance of the Alternative Systems. The environmental performance of each of the alternatives was assessed using life cycle impacts analysis (realized by SimaPro). The following impact categories are selected as environmental criteria: carcinogens, respiratory organics effects, respiratory inorganic effects, climate change, radiation effects, ozone layer depletion, ecotoxicity, acidification/eutrophication, land use, minerals, and fossil fuels. No uncertainty evaluation was performed in this study.

For the evaluation of the environmental impacts, data from the Ecoinvent Report No. 17 on the inventory and emissions, in addition to those of the NREL report and data collected through field research, were used.[20,13] Some indicative emissions, in terms of volume produced per unit, are presented in Table 6 (for the corn stover alternative) and in Table 7 (for the cotton stalks alternative).

Table 6. Indicative Emissions of Corn Stover Ethanol Production System

	value	note
CO_2 biogenic (kg/kg EtOH)	2.93	emissions to air
heat waste emissions (MJ/kg EtOH)	25.85	emissions to air
CO (kg/kg EtOH)	0.000497	emissions to air
methane biogenic (kg/kg EtOH)	3.0×10^{-5}	emissions to air
mineral oil (kg/kg EtOH)	0.000426	disposal
PAH (μg/kg EtOH)	944	emissions to air
PAH (μg/kg EtOH)	32.9	emissions to water
TOC (mg/kg EtOH)	317	emissions to water
VOC (mg/kg EtOH)	2.06	emissions to water
dioxins (ng/kg EtOH)	2.21	emissions to air

The systems' performance per impact category is presented in Table 8. For reasons of comparison, the performance of the system "ethanol 95% in water from wood in distillery, CH" (which describes the ethanol production system from residual wood in Switzerland and is included in the Ecoinvent Database) is also given in the same table.[21]

Table 7. Indicative Emissions of Cotton Stalks Ethanol Production System

	value	note
CO_2 biogenic (kg/kg EtOH)	5.93362	emissions to air
heat waste emissions (MJ/kg EtOH)	45.36	emissions to air
CO (kg/kg EtOH)	0.000833	emissions to air
methane biogenic (kg/kg EtOH)	5.1×10^{-5}	emissions to air
mineral oil (kg/kg EtOH)	0.000426	disposal
PAH (mg/kg EtOH)	1.89	emissions to air
PAH (μg/kg EtOH)	83.8	emissions to water
TOC (mg/kg EtOH)	784	emissions to water
VOC (mg/kg EtOH)	5.25	emissions to water
dioxins (ng/kg EtOH)	3.7	emissions to air

Table 8. Environmental Performance of Production Systems under Evaluation

	EtOH[a] from corn stover	EtOH[a] from cotton stalks	EtOH[a] from wood
carcinogens	0.00449	0.00766	0.00252
respir. organic effects	2.89×10^{-5}	7.51×10^{-5}	1.89×10^{-5}
respir. inorganic effects	0.0266	0.0629	0.012
climate change	0.0122	0.0333	−0.00557
radiation	3.49×10^{-5}	8.5×10^{-5}	1.78×10^{-5}
ozone layer depletion	1.42×10^{-6}	3.81×10^{-6}	1.11×10^{-6}
ecotoxicity	0.00667	0.0122	0.00251
acidification/ eutrophication	0.00548	0.0106	0.00186
land use	0.0639	0.126	0.0423
minerals	0.00138	0.00446	0.00083
fossil fuels	0.00138	0.0967	0.0293
environmental index 99 (EI 99)	0.157	0.354	0.0858

[a]One kilogram EtOH 95% in water at distillery.

The aggregate resultant value for the environmental performance of alternative A (corn stover) according to EI 99 is 0.157, whereas the respective value of alternative B (cotton stalks) is 0.354.

Economic Performance of Alternative Systems. A measure of the economic performance of the alternatives is the operation cost of each production system, including costs for feedstock, labor, maintenance, insurance and taxes, depreciations, and secondary materials. The income from the excess electricity produced is also taken into account (negative cost). The income from ethanol produced is not considered because the calculation basis is 1 kg EtOH (the same for both alternatives). The operation cost of each of the alternatives is presented in Table 9. As the excess electricity generated by the cotton stalks ethanol system is greater in relation to the corn stover one, a decrease in the operational cost is incurred in the former case. Finally, the capital cost is the same for both alternatives; therefore, the capital cost recovery is not taken into account in the analysis performed.

Sustainability Performance of Alternative Systems. According to the preceding analysis, the corn stover ethanol production system is preferable from an environmental performance perspective, while the cotton stalks ethanol system is preferable from an economic perspective. AHP may be used for the purpose of selecting the best alternative based on both criteria by aggregating the performance of each of the alternatives in terms of both criteria and thus determining an overall index U for each of the alternatives. Making the best choice is then straightforward. Table 10 summarizes the performance of each alternative in terms of both criteria. These performance values are the inverse absolute values of the EI 99 index and the total operation cost, respectively (values in parentheses). This adjustment is necessary in order for the following condition to be fulfilled:

Table 9. Alternatives Operation Cost (€/kg EtOH)

	cost of EtOH from corn stover	cost of EtOH from cotton stalks
feedstock	0.1232	0.1958
other variable cost (cost of other raw and secondary materials)	0.0889	0.1415
labor	0.0105	0.0168
maintenance	0.0115	0.0183
insurance and taxes	0.0085	0.0135
depreciations	0.0041	0.0651
excess electricity sales	−0.1312	−0.3510
total	0.1155	0.1000

Table 10. Alternatives Performance on Environmental and Economic Criteria

alternative	environmental criterion (EI 99)	economic criterion (operation cost)
EtOH from corn stover (alternative A)	xA1 = 6.37 (= 1/0.157)	xA2 = 8.66 (= 1/0.1155)
EtOH from cotton stalks (alternative B)	xB1 = 2.82 (= 1/0.354)	xB1 = 10 (= 1/0.1000)

$$\text{Alternative A is preferable to B in respect to criterion } j \text{ if } xAj > xBj$$

where xAj is the performance of alternative A in respect to criterion j.

Following the AHP method, two pairwise comparison matrices must be constructed (one for each criterion) for the determination of each alternatives score against each criterion. The values in these matrices show the decision makers strength of preference between the two alternatives if only one criterion is taken into consideration. On the basis of the values presented in Table 10, the matrices are as in Table 11.

Table 11. Pairwise comparison matrices for score determination

	environmental performance		economic benefit	
	alternative A	alternative B	alternative A	alternative B
alternative A	1	5	1	1/3
alternative B	1/5	1	3	1

The calculated score values of each alternative on the selected criteria are shown in Table 12.

The pairwise comparison matrix for the determination of criteria weights is presented in Table 13. It is assumed that the environmental performance is "weekly more important" than

Table 12. Alternative Scenarios Performance Values

	criteria	
scenarios	environmental performance	economic benefit
alternative A	0.83	0.25
alternative B	0.17	0.75

dx.doi.org/10.1021/sc500249d | ACS Sustainable Chem. Eng. 2014, 2, 2036−2041

Table 13. Pairwise Comparison Matrix for Criteria Weights Determination

	environmental performance	economic benefit
environmental performance	1	2
economic benefit	1/2	1

the economic benefit criterion. This is a reasonable assumption because biofuels come to serve environmental issues at least as much as economic considerations.

Thus, the calculated weights for the environmental performance criterion w1 and for the economic benefit criterion w2 are 0.66 and 0.34, respectively. The resulting overall performance (sustainability index) of each alternative is

$$UA = 0.66 \times 0.83 + 0.34 \times 0.25 = 0.6328$$

$$UB = 0.66 \times 0.17 + 0.34 \times 0.75 = 0.3672$$

Thus, alternative A must be chosen.

In the above analysis, no loss of biomass materials during their storage and transportation is assumed. Actually, biomass losses are observed during these stages and are caused by weathering (leaching, UV degradation, erosion) and biochemical reactions produced by microbes (fermentation), especially in cases where the biomass is stored in the open air.[22,23] This fact incurs in biochemical conversion processes a negative impact, which is both economic and environmental as the more the loss is the more biomass must be collected from the fields. In a recent research, the biomass loss in the case of wrapped round bales of corn stover is found to be on the level of 5%.[24]

In the following, we repeat the analysis assuming that the overall gravimetric dry loss for both alternative feedstocks (corn stover and cotton stalks) during their transport and storage is 5%.

In Table 14, the new results for the alternatives economic and environmental performance values are listed.

Table 14. Revised Alternatives Performance on Environmental and Economic Criteria

alternative	environmental criterion (EI 99)	economic criterion (operation cost)
EtOH from corn stover (alternative A)	$xA1 = 3.52$ (= 1/0.2840)	$xA2 = 8.22$ (= 1/0.1217)
EtOH from cotton stalks (alternative B)	$xB1 = 2.70$ (= 1/0.370)	$xB1 = 9.11$ (= 1/0.1098)

On the basis of the revised values presented in Table 14, the calculated overall alternatives performances are as in Table 15. So, alternative A must be chosen again.

DISCUSSION AND CONCLUSIONS

In the present study, the sustainability of two alternative ethanol production systems was evaluated. The systems chosen will be located in Greece and use corn stover (alternative A) or cotton stalks (alternative B) as the raw material. The technology used (introduced by NREL) includes prehydrolysis of raw material, simultaneous saccharification and cofermentation processes, and product, solids, and water recovery stages. In addition, power is generated, which is used for covering the systems' needs, and the excess is sold in the grid. For the sustainability evaluation, the environmental and economic performances of the alternatives were determined. It has been shown that, based on the assumptions made, ethanol produced from corn stover has a better environmental performance than ethanol produced from cotton stalks. This is mainly due to the former's higher process production yield (in the plant) and to higher raw material yield (in the field). On the other hand, the cotton stalks ethanol system has a better economic performance than the corn stover one due to the bigger excess electricity produced by the former, which is sold to the grid, providing more income. The analytic hierarchy process method was used in order to aggregate the environmental and economic performances of each of the alternatives into an overall (sustainability) index. The analysis has shown (conditioned to the assumptions made) that the corn stover ethanol system is preferable. When taking into account the biomass loss during the transportation and storage, it is shown that the corn stover ethanol system is again more preferable.

Table 15. Alternatives Revised Sustainability Index

	environmental criterion		economic criterion		
	weight	performance	weight	performance	sustainability index (overall performance)
alternative A	0.66	0.86	0.34	0.45	0.7206
alternative B	0.66	0.14	0.34	0.55	0.2794

Concluding the above, it is worth noting the following:

- Ethanol production systems from lignocellulosic materials represent a promising technology that is becoming more mature. In Greece, there exists adequate biomass potential for the development of such a system.
- The environmental performance of both corn stover and cotton stalks ethanol systems is generally good, but it is worse in comparison to ethanol produced from wood.
- The cotton stalks ethanol system exhibits a poorer environmental performance (especially regarding the land use impact category) in relation with the corn stover one because of its low production yield in ethanol (as a consequence of cotton stalks low concentration in cellulose) and its low raw material production yield in cotton fields. On the other hand, the cotton stalks ethanol alternative displays a better economic performance due to increased excess electricity sales, which are due to higher lignin content in relation to the corn stover ethanol system.
- Biomass feedstock loss during transportation and storage causes an increase in the operation cost and in the environmental burdens of the alternative systems because more biomass must be collected from the fields for the production of 1 kg EtOH.

Further research in the area of this study must cover uncertainty issues in order for the critical values for a confident decision-making process to be determined, such as the way the plant's production capacity affects the sustainability of the system, exact determination of the chemical composition of Greek agricultural residues, and feasible ways for the minimization or elimination of collected biomass loss during transportation and storage.

AUTHOR INFORMATION

Corresponding Author

*Tel.: +302108065535. E-mail: evpet@otenet.gr.

Notes

The authors declare no competing financial interest.

REFERENCES

(1) Petrou, E. C.; Pappis, C. P. Biofuels: A survey on pros and cons. *Energy Fuels* **2009**, *23* (2), 1055−1066.

(2) Sassner, P.; Galbe, M.; Zacchi, G. Techno-economic evaluation of bioethanol production from three different lignocellulosic materials. *Biomass Bioenergy* **2008**, *32* (5), 422−430.

(3) von Blottnitz, H.; Curan, M. A. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *J. Cleaner Prod.* **2007**, *15* (7), 607−619.

(4) Klass, D L. *Biomass for Renewable Energy Fuels, and Chemicals*; Academic Press: San Diego, CA, 1998.

(5) *Fifth Assessment Report, Final Draft*; International Governmental Panel for Climate Change, Working Group III, 2014.

(6) BIOLYFE. http://www.biolyfe.eu (accessed 2014).

(7) Clariant. http://clariant.com.

(8) DuPont Biofuel Solutions. http://biofuels.dupont.com/cellulosic-ethanol/nevada-site-ce-facility (accessed 2014).

(9) POET-DSM Advanced Biofuels. http://poet-dsm.com (accessed 2014).

(10) European Biofuels Technology Platform. http://www.biofuelstp.eu/sustainability.html (accessed 2014).

(11) Sims, R. E. H.; Mabee, W.; Saddler, J. N.; Taylor, M. An overview of second generation biofuel technologies. *Bioresour. Technol.* **2010**, *101* (6), 1570−80.

(12) Belton, V., Stewart, T. *Multiple Criteria Decision Analysis: An Integrated Approach*; Springer: New York, 2002.

(13) Aden, A.; Ruth, M.; Ibsen, K.; Jechura, J.; Neeves, K.; Sheehan, J.; Wallace, B.; Montague, L.; Slayton, A.; Lukas, J. *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover*; NREL/TP-510-32438; National Renewable Energy Laboratory: Golden, CO, 2002.

(14) Kaur, U.; Oberoi, H. S.; Bhargav, V. K.; Sharma-Shivappa, R.; Dhaliwal, S. S. Ethanol production from alkali- and ozone-treated cotton stalks using thermotolerant *Pichia kudriavzevii* HOP-1. *Ind. Crops Prod.* **2012**, *37* (1), 219−226.

(15) Shi, J.; Sharma-Shivappa, R. R.; Chinn, M.; Howell, N. Effect of microbial pretreatment on enzymatic hydrolysis and fermentation of cotton stalks for ethanol production. *Biomass Bioenergy* **2009**, *33* (1), 88−96.

(16) *World Summit Outcome, Resolution A/60/1*, adopted by the General Assembly on 15 September 2005. United Nations General Assembly, 2005.

(17) Winston, W. *Operations Research: Application and Algorithms*; Duxbury Press: Belmond, CA, 1994.

(18) Petrou, E.; Mihiotis, A. Design of a factories' supply system with biomass in order to be used as an alternative fuel—A case study. *Energy Fuels* **2007**, *5*, 3718−3722.

(19) Silverstein, R. A.; Chen, Y.; Sharma-Shivappa, R. R.; Boyette, M. D.; Osborne, J. A comparison of chemical pretreatment methods for improving saccharification of cotton stalks. *Bioresour. Technol.* **2007**, *98*, 3000−3011.

(20) Jungbluth, N.; Chuadacoff, M.; Dauriat, A.; Dinkel, F.; Doka, G.; Faist Emmenegger, M.; Gnansounou, A.; Shleiss, K.; Spielmann, M.; Stettler, C.; Sutter, J. *Life Cycle Inventories for Bioenergy*; Ecoinvent Report No. 17; Swiss Centre for Life Cycle Inventories: Dubendorf, CH, 2007.

(21) The ecoinvent Database. http://www.ecoinvent.org/database (accessed 2014).

(22) Wiselogel, A. E.; Agblevor, F. A.; Johnson, D. K.; Deutch, S.; Fennell, J. A.; Sanderson, M. A. Compositional changes during storage of large round switchgrass bales. *Bioresour. Technol.* **1996**, *56* (1), 103−109.

(23) Khanchi, A.; Jones, C. L.; Sharma, B.; Huhnke, R. L. Characteristics and compositional change in round and square switchgrass bales stored in South Central Oklahoma. *Biomass Bioenergy* **2013**, *58*, 117−127.

(24) Storage and Processing of Corn Stover Eastern Iowa Mid-Scale Trials: Practical Considerations. http://bioenergy.illinois.edu/news/biorefinery/pp_cecava.pdf (accessed 2014).