Life Cycle Assessment of Cellulosic Ethanol and Biomethane Production from Forest Residues

Shaobo Liang, Hongmei Gu,* and Richard D. Bergman

There is a strong need to manage low-value forest residues generated from the management practices associated with wildfire, pest, and disease control strategies to improve both the environmental and economic sustainability of forestlands. The conversion of this woody biomass into value-added products provides a great opportunity to benefit both the environment and economy. This study aimed to assess the environmental impacts of converting forest residues into two renewable fuels, cellulosic ethanol and biomethane, by different biochemical conversion pathways. The energy balances and environmental impacts, including acidification, eutrophication, global warming, and photochemical ozone formation, of the two biorefinery approaches were addressed. This work illustrated the advantages of converting forest residues into biomethane from energy and environmental perspectives. The tradeoff between the economic benefits and potential environmental issues need to be carefully considered.

Keywords: Anaerobic digestion; Cellulosic ethanol; Forest residue; Global warming; Life cycle assessment

*Contact information: USDA Forest Service, Forest Products Laboratory, One Gifford Pinchot Drive Madison, WI 53726 USA; *Corresponding author: hongmeigu@fs.fed.us*

INTRODUCTION

The global dependence on energy from fossil fuels has resulted in substantial greenhouse gas (GHG) emissions and an impact on global warming (IPCC2014). These energy and environmental concerns have stimulated intensive research and development efforts into alternative renewable energies, including woody biomass (CORRIM 2012; González-García *et al*. 2012).Woody biomass is renewable and can be sustainably sourced. Additionally, the carbon dioxide released from the burning of woody biomass can be re-absorbed during forest growth. Biomass-derived fuels have the potential to be carbon dioxide negative if the carbon dioxide generated during the conversion process can be sequestered (Anderson and Peters 2016; Grant 2017). U.S. forest management activities, such as forest thinning and timber harvest, produce large quantities of woody biomass that can be used as feedstock for the production of renewable fuels and chemicals (Tilman *et al*. 2009; Jakes *et al*. 2016; Rudie *et al*. 2016). Forest biomass represents 25% to 30% of the annual biomass available in the U.S. for conversion into bio-based fuels, bio-based chemicals, and bioproducts in general (Rudie *et al*. 2016). These forest residues can contribute to a secure national energy source and reduce GHG emissions (Gu and Bergman 2017). It has been estimated that woody biomass-derived renewable fuels can reduce more than 60% of the lifecycle GHG emissions compared with petroleum-based gasoline or diesel used as transportation fuel (Schnepf and Yacobucci 2013).

Cellulosic ethanol and biomethane are two popular renewable fuels that are generated through two biochemical conversion processes. These two biorefinery processes

have some similarities, such as the hydrolysis of polymeric carbohydrates into small sugar molecules, but essentially they are two different approaches. Cellulosic ethanol production involves the chemical and enzymatic breakdown of cellulose and hemicellulose into simple mono-sugars, which is followed by alcoholic fermentation, ethanol distillation, and purification. The lignin fraction can be used for steam and electricity generation to support other facilities within the system unit. Biomethane production includes the anaerobic digestion (AD) of complex carbohydrates, fats, proteins, and other carbon-rich materials into short chain organic compounds by a variety of anaerobic microorganisms and biogas, which is followed by impurity gas/water removal and methane purification. The solid coproduct-containing non-degraded lignin, cellulose, and hemicellulose can be combusted onsite to generate steam and electricity. Additionally, biogas that has not been deep cleaned can also be used for steam generation within the facility. The AD system is a technically effective, but time-consuming process, and usually it requires long reaction times of 10 to 40 d (Sawatdeenarunat *et al*. 2015). Although cellulosic ethanol and biomethane have different forms, liquid and gaseous, respectively, the embodied energies of the two fuels generated from the same quantity of biomass are comparable, and they can both be utilized as fuel for vehicles (Börjesson and Mattiasson 2008). Theoretically, 1 kg of glucose can be converted into 0.511 kg of ethanol or 0.414 $m^3$of methane through biochemical conversion (Krich *et al*. 2005), which equals 15.18 and 16.39 MJ of energy, respectively. Given these similar energy contents, it is appealing to further explore the environmental performance of these two bioprocesses when converting woody biomass into fuels. Valuable information for decision makers could be provided through the comparison of these two technologies for the better and more efficient utilization of forest residues.

A life cycle assessment (LCA) is an internationally accepted methodology to assess the environmental impacts of products, processes, or services from the perspective of the holistic life cycle (ISO14040 2006; ISO 14044 2006). A LCA is composed of four phases: 1) the goal and scope, which details the purpose and extent of the project; 2) a life cycle inventory (LCI), which covers data collection and quantification of inputs and outputs within the defined system boundaries; 3) a lifecycle impact assessment (LCIA), which aggregates the LCI outputs to estimate specific environmental and human health impacts; and 4) interpretation that clarifies what is happening and what can be done to increase the environmental performance of the studied product. Different LCA studies on the production of cellulosic ethanol and biogas have been done previously (Berglund and Börjesson 2006; Nguyen and Gheewala 2008; Mu *et al*. 2010; Collet *et al*. 2011; González-García *et al*. 2012). However, there is a lack of comparative study on the environmental performance of the two technologies (Patel *et al*. 2016). In this paper, a comparative LCA study on cellulosic ethanol and biomethane production from forest residues was conducted using OpenLCA software, which is easily accessible to the public. The energy balances and environmental performances were analyzed with the LCI outputs from the models built in OpenLCA.

METHOD

Goal and Scope

The primary goal of this study was to compare the environmental impacts associated with cellulosic ethanol and biomethane production from forest residues through two different biochemical conversion pathways. The functional unit for this analysis was

defined as 1 ton of forest residue converted into commercial grade of >99% purity cellulosic ethanol or >96% purity biomethane. Mass and energy accounting data were collected from the peer-reviewed literature and normalized based on this functional unit within the system boundaries, according to the Consortium for Research on Renewable Industrial Materials (CORRIM) guidelines (CORRIM 2010). The details are described in the following sections. To conduct a distinct comparison of the environmental impacts of the two processes, the LCI flows and LCIA outcomes for cellulosic ethanol and biomethane production from gate-to-gate, including biochemical conversion and products distillation/ purification, were modeled in accordance with ISO 14040 (2006) and ISO 14044 (2006) environmental management standards, respectively.

System Boundary and Unit Processes

The system boundary was defined as gate-to-gate for the two proposed biorefinery systems, which each had a processing capacity of 500 t of biomass feedstock/d, as illustrated in Fig. 1.

The comparison in this study included only the biochemical conversion, cogeneration, products distillation, and purification processes. The upstream processes for both production systems were assumed to be identical, and thus they were not considered in this analysis. The end of life cycle management activities, such as direct use of biofuels, wastewater discharge, solid waste disposal, and onsite air emissions, were also excluded from the system.

The biomass feedstock considered in this study was forest residues from U.S. national forests with a mix of conifer species that was dominated by Lodgepole pine (*Pinus contorta*), Douglas fir (*Pseudotsuga menziesii*), and Ponderosa pine (*P. ponderosa*). The moisture content of this biomass ranges from 10% to 50%. This biomass presents a rich-carbohydrate composition that is 39% to 55% cellulose and 18% to 33% hemicellulose (Youngblood *et al*. 2010; Lam *et al*. 2013; Wei *et al*. 2015), and can be converted into a variety of useful fuels and chemicals, such as cellulosic ethanol and biomethane. These two renewable fuels are currently being studied extensively as important substitutes for future clean energy (Kumar and Murthy 2011; Tagliaferri *et al.* 2016). For cellulosic ethanol conversion, the focused unit processes were: i) acid hydrolysis of the biomass (22% solid content) with 0.5% sulfuric acid and 190 °C steam for 10 min to break down the cellulose structure and release hemicellulose and other compounds; ii) enzymatic hydrolysis with simultaneous saccharification and co-fermentation at 30 °C for 7 d for ethanol production; and iii) distillation and dehydration to purify and concentrate the ethanol up to a 99% volume fraction (Aden *et al*. 2002). The ratios for conversion of cellulose and hemicellulose in the woody biomass into end-product ethanol were assumed to be 86% and 77%, respectively, which was based on previous studies (Aden *et al*. 2002; Mu *et al*. 2010). This study adopted the methodology developed by the U.S. Department of Energy National Renewable Energy Laboratory because the process has been discussed extensively in the literature (Aden *et al*. 2002; Nguyen and Gheewala 2008; Mu *et al*. 2010; Kumar and Murthy 2011; González-García *et al*. 2012; Kumar and Murthy 2012). For biomethane conversion, the modeled unit processes included: i) anaerobic decomposition at 35 °C for 40 d of carbohydrates into small molecules and the end products methane and carbon dioxide; and ii) biogas purification to remove carbon dioxide, water vapor, and other impurities to increase the biomethane content up to a 96% grade. The conversion ratio was estimated to be 75% of the maximum biological potential yield (Collet *et al*. 2011). The model development was based on the studies by Berglund and Börjesson

(2006), Collet *et al*. (2011), and Rehl and Müller (2011). Other scenarios, such as the use of lignin and un-reacted carbohydrates for steam and electricity production through an onsite cogeneration system and the use of animal waste to replace nutrients demanded in the AD process, were also modeled as alternative scenarios. Scenario 1 (S1) was the base case with no cogeneration from coproducts, while scenario 2 (S2) incorporated the burning of coproducts for steam and electricity production *via* a cogeneration unit. Additionally, the human labor and LCA of the infrastructure and machinery were outside the system boundaries, and therefore were not included in this model.

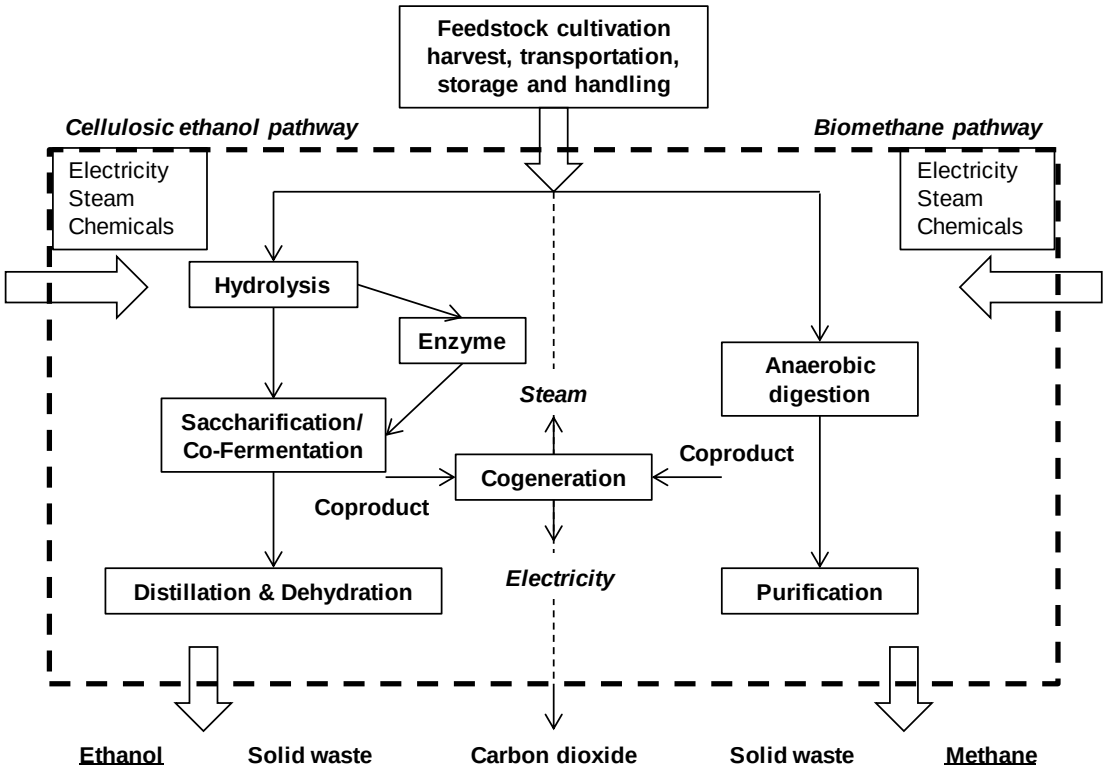

Fig. 1. System boundaries of the two conversion pathways for cellulosic ethanol and biomethane production

Life Cycle Inventory

Table 1 summarizes the mass and energy balances for utilizing 1 t of woody biomass for cellulosic ethanol and biomethane production. These data were compiled from related studies (Berglund and Börjesson 2006; Mu *et al*. 2010; Collet *et al*. 2011; Rehl and Müller 2011; González-García *et al*. 2012; NREL 2016). The comparative LCI model for the two conversion processes was built in free open-source LCA software OpenLCA (GreenDelta GmbH, Berlin, Germany) to estimate the environmental impacts. The chemical emission and resource used that contribute to an impact category are multiplied by a characterization factor that expresses the relative contribution. For example, the characterization factor for carbon dioxide in the global warming impact category can be equal to 1, while the characterization factor for methane and nitrogen oxide can be 25 and 298, respectively. The detailed analysis and full characterization list can be found at the TRACI 2.0 method (Bare 2011).

Table 1. Mass and Energy Flows for Cellulosic Ethanol and Biomethane Production Utilizing Woody Biomass

Item	Unit	Cellulosic ethanol production	Biomethane production
Inputs*			
Biomass	t	1.00	1.00
Cellulase enzyme	kg	8.75	--
Sulfuric acid	kg	34.50	--
Lime	kg	25.35	40.00
Diammonium phosphate	kg	1.74	9.34
Corn steep liquor	kg	13.85	18.40
Electricity	kWh	276.5	411.0
Steam	GJ	5.27	1.90
Outputs			
Ethanol	kg	283.0	--
Methane	m^3	--	205.5
Coproducts	kg	327.0	406.0
Solid waste	kg	86.4	35.0
Carbon dioxide	m^3	270.7	403.7

* The input parameters were normalized according to Berglund and Börjesson (2006), Collet *et al*. (2011), González-García *et al*. (2012), Mu *et al*. (2010), and Rehl and Müller (2011).

RESULTS AND DISCUSSION

Energy Accounting

The energy balance usually accounts for the energy flow across the system boundary that defines the difference between the energy contents of the biofuel outputs and the fossil fuel energy consumed to produce the end products (Gu and Bergman 2016). As shown in Table 2, the total biofuel energy content in the cellulosic ethanol production process for S1 was 8,320 MJ/t biomass consumed, whereas a total of 6,271 MJ of fossil fuel energy inputs (steam and electricity) were needed to produce this amount of cellulosic ethanol energy. For the biomethane production process, only 3,381 MJ of fossil fuel energy inputs were required to convert 1 t of biomass into 7,805 MJ of biomethane, which was 2.16 times the net energy gain of the cellulosic ethanol production process without onsite cogeneration. The fossil energy replacement ratio (FERR) is an indicator that defines the ratio of biofuel energy output from a system over the fossil fuel energy input into a system (Sheehan *et al*. 2003; Geottemoeller and Geottemoeller 2007). In this study, the FERR was 1.33 and 2.31 for the cellulosic ethanol and biomethane production processes, respectively. This meant that for every 1 MJ of fossil fuel energy input into the cellulosic ethanol and biomethane production systems, 1.33 and 2.31 MJ of biofuel energy output were generated, respectively.

When considering the onsite cogeneration in S2, it was assumed the conversion efficiencies for steam production from the coproducts and electricity production from the steam was 75% and 40%, respectively (Kumar and Murthy 2012). Under such conditions, all of the steam demands in both processes can be met. Additionally, cogeneration can further offset 27 kWh of the electricity demands (277 kWh for S1 and 250 kWh for S2) in the cellulosic ethanol production process and generate an excess of 93 kWh of electricity in the biomethane production process. It should be noted that this comparison should not be conducted for fuels with different energy qualities, such as coal and electricity (Dale 2007; Kumar and Murthy 2011). Although both ethanol and biomethane can be used as

fuel for vehicles, the net energy use calculation is a single indicator for these alternative fuels. The environmental performance, such as GHG emissions and climate change impacts, are more informative for such comparisons.

Table 2. Energy Balance of the Two Conversion Processes Utilizing Woody Biomass with and without Onsite Cogeneration

Source	Energy value		Unit	
Biomass	18.05		MJ/kg	
Cellulose	17.00		MJ/kg	
Hemicellulose	16.63		MJ/kg	
Lignin	21.13		MJ/kg	
Ethanol	29.7		MJ/kg	
Methane	39.4		MJ/m^3	
Electricity	3.6		MJ/kWh	
Energy balance	Cellulosic ethanol production		Biomethane production	
	S1*	S2**	S1*	S2**
Biomass energy (MJ)	18,050	18,050	18,050	18,050
Thermal energy (MJ)	5,274	--	1,901	--
Electricity use (kWh)	277	250	411	-93
Biofuel energy output (MJ)	8,320	8,320	7,805	7,805
Coproduct energy (MJ)	7,348	--	8,584	--
Net fossil energy input (MJ/t)	6,271	901	3,381	-335
Net energy gain (MJ/t)	2,049	7,419	4,424	8,919
Fossil energy replacement ratio	1.33	--	2.31	--
* Scenario S1 with no cogeneration ** Scenario S2 with cogeneration				

Environmental Performance

Figure 2 shows a comparison of the four most important environmental impacts, acidification (kg SO_2 eq), eutrophication (kg N eq), global warming (GW, kg CO_2 eq), and photochemical ozone formation (kg O_3 eq), for the two conversion processes and two scenarios, S1 and S2. The onsite cogeneration system showed substantially lower environmental impacts for three of the four impacts for both processes, and there was no change in eutrophication. As illustrated in Fig. 2, the biomethane conversion process exhibited lower impacts than the cellulosic ethanol production process for all of the environmental effects, except eutrophication. For example, it was observed that the acidification and photochemical ozone formation effects from biomethane production were approximately 26% lower than for cellulosic ethanol production. The positive contributions to acidification were mainly from the electricity and steam production that released sulfuric oxide and nitrogen oxide. The difference between the two processes was mainly because of enzyme production, which contributed to 16% of the total acidification impact in the cellulosic ethanol production process. Additionally, it was observed that the GW impact was more than 45% lower in the biomethane production process. The GHG emissions were calculated as carbon dioxide equivalent (CO_2 eq) for the carbon dioxide, methane, and dinitrogen monoxide emissions from electricity, steam, and limestone production. Although high biogenic carbon dioxide emissions were observed in both conversion processes, the release of biogenic carbon dioxide to the atmosphere from the burning and biodegradation of woody biomass was considered to be carbon neutral because the forest carbon growth was equal to or greater than the carbon lost through sustainable forest harvesting practices (Lippke *et al*. 2011). In addition, uncertainties, such as methane

potentially leaking from the biomethane production process, may also result in a substantial GW impact. The eutrophication indicator for the biomethane conversion process was approximately five times higher than for the cellulosic ethanol production process, which was mainly because of the phosphorus and nitrogen fertilizers used. Typically, the AD process uses animal waste to provide nutrient sources and adjust the carbon nitrogen balance, and the biogas productivity can also be remarkably improved through co-digestion (Sawatdeenarunat *et al*. 2015). By using waste streams to offset the nutrients in the AD process, the eutrophication impact can be decreased to only 5% of that in the cellulosic ethanol production process. It was concluded that the biomethane production process has a greater potential for lower environmental impacts compared with the cellulosic ethanol production process.

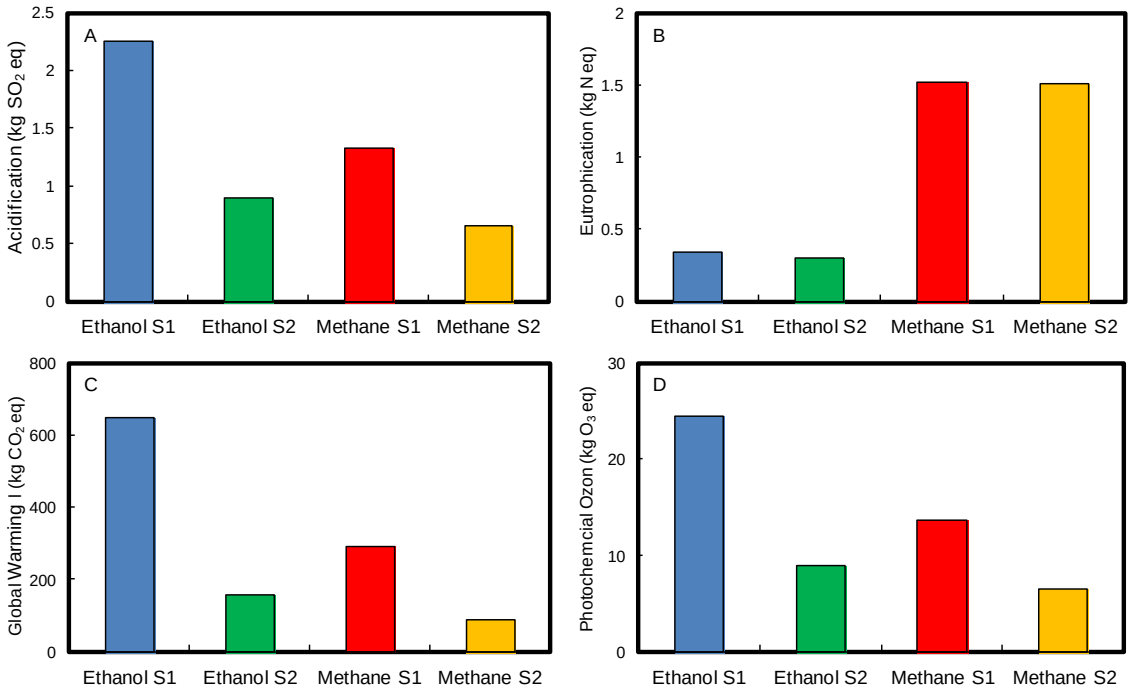

Fig. 2. Environmental impacts of acidification (A), eutrophication (B), GW (C), and photochemical ozone formation (D) for the two processes with S1 (no cogeneration) and S2 (with cogeneration)

In addition, the use of cellulosic ethanol and biomethane as fuel in vehicles has been put into practice, and previous LCA studies have indicated that both cellulosic ethanol and biomethane exhibited great advantages compared with traditional fuels from an environmental perspective (Beer *et al*. 2000; Uusitalo *et al*. 2013). However, the average market value of methane (as natural gas) is approximately one-quarter that of ethanol per MJ, and only a slightly lower production cost for biomethane than for cellulosic ethanol was reported (Patterson *et al*. 2011).

Biomethane has great potential to meet the national renewable energy goals, strengthen the economy, and reduce GHG emissions (USDA 2014). However, promoting biomethane production and utilization may also demand more focus on technological innovation to reduce operational costs with government support for its production and development of gas for vehicles.

Limitations

Due to insufficient information on the two conversion technologies investigated, this study only focused on theoretical analysis and assumptions. The production, maintenance, and disposal of equipment as well as wastewater discharge in these systems were considered outside the scope of the LCA. In addition, human labor and infrastructure data and impacts were outside the scope as these technologies would be considered energy-intensive. Further research that includes the consideration of all these limitations would be of interest to consider in future studies.

CONCLUSIONS

1. The biomethane production process was found to have a relative higher net energy gain and lower acidification, GW, and photochemical ozone formation impacts than cellulosic ethanol production from forest residues based on the evaluation of energy balances and environmental performances using LCA tools.
2. Policy makers need to consider the tradeoff between environmental costs and social and economic benefits when producing renewable fuels.
3. Additionally, governmental subsidies for biomethane would be desirable to promote its production and utilization as fuel for vehicles.

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