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Research paper

Ethanologens vs. acetogens: Environmental impacts of two ethanol fermentation pathways

Erik Budsberg [a, *], Jordan Crawford [a], Rick Gustafson [a], Renata Bura [a], Maureen Puettmann [b]

[a] University of Washington, School of Environmental and Forest Sciences, Box 352100, Seattle, WA 98195-2100, USA
[b] WoodLife Environmental Consultants, 8200 NW Chaparral Dr., Corvallis, OR 97330, USA

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ABSTRACT

Bioconversion production of ethanol from cellulosic feedstock is generally proposed to use direct fermentation of sugars to ethanol. Another potential route for ethanol production is fermentation of sugars to acetic acid followed by hydrogenation to convert the acetic acid into ethanol. The advantage of the acetogen pathway is an increased ethanol yield; however, using an acetogen requires the additional hydrogenation, which could substantially affect the life cycle global warming potential of the process. Assuming a poplar feedstock, a cradle to grave Life cycle assessment (LCA) is used to evaluate the environmental impacts of an acetogen based fermentation pathway. An LCA of a fermentation pathway that uses ethanologen fermentation is developed for comparison. It is found that the ethanologen and acetogen pathways have Global Warming Potentials (GWP) that are 92% and 46% lower than the GWP of gasoline, respectively. When the absolute GWP reduction compared to gasoline is calculated using a unit of land basis, the benefit of the higher ethanol yield using the acetogen is observed as the two pathways achieve similar GWP savings. The higher ethanol yield in the acetogen process plays a crucial role in choosing a lignocellulosic ethanol production method if land is a limited resource.

1. Introduction

In an effort to find a substitute for petroleum based liquid transportation fuels many countries are turning to biofuels. The newest form of these biofuels, also known as the second generation or cellulosic biofuels, have received considerable attention [1,2]. In the United States, yearly targets for production of cellulosic biofuels have been set at 3.79 hm^3 liters in 2013 and ramp up to 60.6 hm^3 liters in 2022 (Energy Independence and Security Act (EISA)) [3]. Currently the yearly minimum requirements have not been met as commercial cellulosic ethanol plants are only now starting to come online. A diverse range of feedstocks along with optimal conversion technologies will be required to meet future yearly targets.

Short Rotation Woody Crops (SRWC), such as *Populus* (poplar) and *Salix* (willow), present an attractive option for diversifying and expanding biomass available for biofuel production. Used in the past for various products such as fuel wood, lumber, and paper, these well-established crops present good characteristics for biofuel use. In general they require little fertilizer input, can be cultivated on marginal lands, have the ability to resprout after multiple harvests, and have a high biomass production [4–7]. The lignocellulosic material in Poplar wood can also be fractionated without extensive pretreatment [8] and hardwoods don't exhibit the recalcitrance reported in softwoods [9].

Appropriate conversion technologies must be used to convert the lignocellulosic material in SRWC to ethanol. A bioconversion process developed at the National Renewable Energy Laboratory (NREL) [10,11] is one prominent process proposed in the last decade. This process can be broken down into a few key steps

Abbreviations: AP, acetogen pathway; EISA, Energy Independence and Security Act; EP, ethanologen pathway; GWP, global warming potential; GHG, greenhouse gas; GREET, greenhouse gases, regulated emissions, and energy use in transportation; ILUC, indirect land use change; IPCC, Intergovernmental Panel on Climate Change; ISO, International Standards Organization; LCA, life cycle assessment; LCI, life cycle inventory; NREL, National Renewable Energy Laboratory; SRWC, short rotation woody crop; SMR, steam methane reforming; TRACI, tool for the reduction and assessment of chemicals and other environmental impacts.

* Corresponding author.
E-mail addresses: budsberg@uw.edu (E. Budsberg), jtcraw@uw.edu (J. Crawford), pulp@uw.edu (R. Gustafson), renatab@uw.edu (R. Bura), Maureen.puettmann@woodlifeconsulting.com (M. Puettmann).

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beginning with a pretreatment step using chemical and/or physical processes that exposes cellulose and other carbohydrates. The cellulose is hydrolyzed to glucose using either enzymes or acid. An ethanologen (yeast or bacteria) ferments the glucose and other sugars to ethanol. The lignin and unfermented carbohydrates are burned to produce process steam and electricity. In the NREL process, there is an excess of electricity that can be sold to the electrical grid. Using the NREL platform researchers have reported ethanol yields from bone dry wood range from 310 L t^{-1} to 429 L t^{-1} and excess electricity generation of 0 MJ–0.2 MJ per mega joule of ethanol [6,7,12–14]. The range in values is related to assumptions made regarding conversion rates (polymers to monomers, sugars to ethanol) and the amount of biomass used for electricity production (i.e. if the biorefinery is designed with a turbine).

The use of an ethanologen in the fermentation step is potentially an inefficient way to produce ethanol. For every mole of glucose consumed by an ethanologen one mole of ethanol and one mole of CO_2 are produced. The production of CO_2 limits the theoretical carbon efficiency at 67% of carbon in sugars going to ethanol [15]. A different fermentation pathway can be used to increase carbon efficiency. An acetogen, an organism that ferments sugars to acetic acid, can potentially make the bioconversion process more efficient. These organisms will only produce acetic acid as it consumes glucose (and other sugars) [16]. The acetic acid produced can then be converted to ethanol using catalytic hydrogenation. The end result is a much higher yield of ethanol per tonne of biomass [17].

An increased ethanol yield through the use of an acetogen is beneficial, but environmental impacts associated with this process must be investigated. In this study, Life Cycle Assessment (LCA) is used to investigate the cradle to grave environmental impacts that would result from a biorefinery that uses an acetogen fermentation process to convert poplar biomass to ethanol for use in an automobile. An LCA of a comparable system using a traditional ethanologen fermentation pathway is developed as well. Both fermentation pathways are compared to gasoline produced in 2005, the baseline set by EISA [3].

2. Methods

2.1. Goal and scope

LCA is used to investigate the environmental impacts that result from growing poplar trees and converting the lignocellulosic material into ethanol for use as fuel in an automobile over a 21 year time horizon. A 21 year time horizon is chosen so as to include the lifespan of a poplar tree farm (site preparation, nursery operations, and six - three year coppice cycles). The LCA approach assigns resource consumption and emissions into specific categories that allows for a detailed analysis of how the biofuel pathways could affect the environment. Overall impacts are determined as well as identification of processes within each model that contribute to a given impact category. The structure and proper methods for conducting an LCA are set by International Standards Organization (ISO) 14040 & 14044 [18,19] and every attempt was made to follow this design. The LCA models are developed in SimaPro v.7.3.3 LCA software. Unit processes used within each model come from the United States Life Cycle Inventory [20], EcoInvent [21], literature, and the private sector. In all cases electricity was assumed to come from the 2012 U.S. national grid [22]. Details regarding electrical grid makeup, data collection, data quality, and all unit processes used in the life cycle modeling of each fermentation pathway are provided in the supplementary material.

2.2. Functional unit and impact calculation methods

This study includes the investigation of two different functional units. The first is a functional unit of 1 MJ (MJ) of ethanol. Using a unit of energy is common practice in biofuel LCAs as it allows for the comparison of different types of fuels regardless of their respective energy densities [1,2]. The HHV energy densities for ethanol and gasoline are assumed to be 29.8 MJ kg^{-1} and 46.5 MJ kg^{-1} respectively [23]. Environmental impacts assessed on a per MJ basis include the 100 year global warming potential (GWP), fossil fuel use, and freshwater use. The 100 year GWP is measured as CO_2 equivalence by mass and is calculated using The Tool for the Reduction and Assessment of Chemicals and other environmental Impacts (TRACI) [24]. Biogenic CO_2 and non-biogenic CO_2 are both included in the results. Biogenic CO_2 refers to carbon that is part of the natural carbon cycle. This includes CO_2 sequestration in the poplar biomass and CO_2 produced from combustion of biomass. Non-biogenic CO_2 refers to CO_2 emissions produced from fossil fuel combustion. Biogenic CO_2 is sometimes omitted when calculating the GWP as this CO_2 is part of the carbon cycle, but is included in this study so that a full carbon mass balance can be presented. Biogenic and non-biogenic CO_2 emissions are identified and tracked separately so that the contribution of the emission can be identified. Fossil fuel use is determined by summing all fossil fuel inputs (coal, natural gas, crude oil) in terms of energy content (MJ). Freshwater use is calculated for the life cycle of each fuel by summing all freshwater withdrawals in the life cycle inventories (LCI). Life cycle inventory water use data used in this study does not identify freshwater sources (groundwater, surface water, or watersheds) and only identifies the total amount of freshwater used (water withdrawal). A more detailed analysis identifying consumptive and non-consumptive water use, water depletion of reservoirs, or changes to water quality in a given watershed is beyond the scope of this study. The environmental impacts of the ethanol production pathways assessed using a per MJ functional unit are compared to each other and gasoline produced in 2005. Life cycle data for 2005 gasoline is obtained using The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model v1.2.0.11425 (GREET).

The GWP is also assessed using a functional unit of one hectare (ha) of land. This functional unit is used to assess the absolute reduction in GWP of the two fermentation pathways if the ethanol produced is used to replace gasoline. Fewer biofuel LCAs have used feedstock land area as the functional unit [1,2], but it provides valuable insight into the best use of limited land resources to reduce greenhouse gas emissions [25]. The benefit of an increased ethanol yield may not be fully captured when emissions are referenced to a MJ of fuel and then used to make relative comparisons to gasoline. A higher yielding conversion process may result in greater absolute GWP savings for a given land basis by simply producing more fuel than another method. Relating the GWP to the land area provides an alternative method to analyze potential life cycle emissions and has been used in previous studies to compare carbon impacts for a variety of biomass based products [25–27]. Results of the land functional unit analysis in this research are used to make comparisons between the two ethanol production pathways.

The land functional unit (GWP savings for ethanol per hectare) calculation performed here is similar to the method reported in Evans et al. [27]. The GWP savings is calculated as follows:

$$\text{GWP savings} = \left(\text{Energy yield}_{\text{ethanol}} * \left(\text{GWP}_{\text{gasoline}} - \text{GWP}_{\text{ethanol}}\right)\right) \Big/ 1\,000\,000 \quad (1)$$

where GWP savings is the difference between GWP of gasoline displaced and GWP of ethanol (t ha^{-1}), energy $\text{yield}_{\text{ethanol}}$ is the