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Evaluation of the environmental impacts of ethanol production from sweet sorghum

Ife A. Olukoya [a], Danielle Bellmer [b], James R. Whiteley [a], Clint P. Aichele [a,*]

[a] School of Chemical Engineering, Oklahoma State University, 423 Engineering North, Stillwater, OK 74078, USA
[b] Department of Biosystems and Agricultural Engineering, Oklahoma State University, 108 FAPC, Stillwater, OK 74078, USA

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ABSTRACT

Ethanol from biomass feedstocks has the potential to reduce greenhouse gas emissions for fuel production. This work calculates the potential environmental impact from the production of ethanol from sweet sorghum using several processing options. The following three processing options were evaluated: 1) a farm scale decentralized option where all steps except the dehydration are performed on the farm, 2) a semi-centralized process where distillation and dehydration are performed at a biofuel refinery, and 3) a centralized process where sorghum stem is transported to a facility where all processing is performed. Results show that a centralized process where sweet sorghum stem is transported to a processing facility to produce ethanol has significant negative environmental impacts when compared to corn ethanol and other processing options. The centralized option resulted in a 62% increase in GHG emissions and a 50% increase in non-renewable energy use compared to corn ethanol. When the decentralized and semi-centralized options were compared to corn ethanol production, GHG emissions were reduced by 39% and 25% respectively. Non-renewable energy use reductions were 27% in the decentralized process and a 15% reduction in the semi-centralized process.

Introduction

Surging energy demand, fossil fuel depletion, increased climate awareness, and energy security concerns have resulted in research on alternative sources of energy with biomass being one of those sources. Biomass feedstocks have the potential to replace conventional fuels and reduce greenhouse gas (GHG) emissions. Common biomass feedstocks include corn, wheat, sugarcane, sugar beets, and sweet sorghum (Bai et al., 2010). Increased crop yields, improved fertilizer efficiency and innovation in biomass conversion processes are leading to improved profitability of ethanol biofuel production (Cassman and Liska, 2007).

Annual ethanol production in the United States in 2012 was 12.7 billion gallons (U.S. Ethanol Production and the Renewable Fuel Standard RIN Bank), most of which was produced from corn. Because corn is the most dominant biomass feedstock in the United States, there have been numerous life cycle assessments (LCAs) performed on corn ethanol production (Kim et al., 2009; Liska et al., 2009; Wang et al., 2007; Spatari et al., 2005; Adler et al., 2007). These studies have focused primarily on GHG emissions and fossil fuel use and have not focused on land usage, respiratory effects, and land and water pollution. Sweet sorghum is a high energy, drought resistant crop that can thrive in a variety of climates and soil conditions. When compared to corn, sweet sorghum could be a potentially more attractive biomass feedstock because of its low nutrient and water requirements. There are studies on the production of biofuels from sweet sorghum. Cai et al. (2013) investigated the life-cycle energy use and GHG emissions from the production of ethanol from grain sorghum, forage sorghum and sweet sorghum, the results are summarized in Table 1. Köppen et al. (2009) performed a screening assessment that analyzed the GHG emissions and energy use along the entire life cycle of the sweet sorghum ethanol process for different production and use scenarios. There has been a major research effort at Oklahoma State University to investigate feasible approaches for ethanol production from sweet sorghum, and this study is an addition to the research effort. Agricultural production of biomass can be an environmentally intensive process; therefore, the environmental sustainability of biofuel production processes must be assessed. Land use can be intensive, there are emissions to air, water, and soil from the use of fertilizers and plant protection, and harvesting and processing can be energy intensive (von Blottnitz and Curran, 2007).

Process description

Three processing options are evaluated in this work: 1) a farm scale decentralized process where all steps except the dehydration are performed on the farm, 2) a semi-centralized process where the distillation and dehydration are performed at a biofuel refinery, and 3) a centralized process where the sorghum stem is transported to a

* Corresponding author. Tel.: +1 405 744 9110; fax: +1 405 744 6338.
E-mail address: clint.aichele@okstate.edu (C.P. Aichele).

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Table 1
GHG emissions and energy use for different sorghum feedstocks, per MJ of ethanol produced.

Feedstock	GHG emissions (kg CO_2/MJ)	Fossil energy use (MJ/MJ)
Grain sorghum	0.04–0.06	0.2–0.5
Sweet sorghum	0.03	0.2–0.3
Forage sorghum	0.05	0.4

facility where the juice extraction, fermentation, distillation and dehydration are performed.

Cultivation and harvesting

In this analysis, sweet sorghum is grown without the use pesticides, insecticides, and irrigation. The process for producing ethanol from sweet sorghum includes a modified forage chopper that harvests and cuts the sweet sorghum stalk down to six to eight inch billets. In the centralized processing option, billets are transported to a processing facility where the remaining steps are performed.

Juice extraction and fermentation

The billets are sent to a screw press that extracts the juice. Bagasse is a by-product of this process, in the decentralized and semi-centralized options; bagasse is dried and fed to cattle. In the centralized process, the bagasse is burned to produce steam for the distillation column and electricity for the process. The juice is fermented using *Saccharomyces cerevisiae* in polyethylene tetraphthalate vessels where ethanol is produced (Kundiyana et al., 2010). In the semi-centralized process, the ethanol produced after fermentation is transported to a processing facility where the distillation and dehydration are performed.

Distillation and molecular sieve

A distillation column is used to produce 95 wt.% ethanol, the decentralized and semi-centralized processes use natural gas to provide steam for the distillation column while the centralized process uses bagasse. The 95 wt.% ethanol produced in the decentralized process is transported to a facility where ethanol dehydration occurs. A molecular sieve is used to dehydrate the ethanol produce 99.7 wt.% anhydrous ethanol.

Materials and methods

Life cycle assessment

Life cycle assessment (LCA) is a methodology for evaluating the potential environmental associated to product systems. The framework also leads to technological innovation by focusing research efforts on the parts of the process that are energy and environmentally intensive. This technique identifies areas of environmental impact, and it provides quantitative data that facilitates compliance with environmental regulations. It can also assist in informing decision and policy makers in areas of environmental protection (ISO, E., 14040: 2006, 2006). An LCA investigation requires a goal and scope definition, inventory analysis, impact assessment, and an interpretation of the results, as outlined by ISO 14040:2006 (2006) and ISO 14044:2006 (2006).

Software used

This work utilizes the IMPACT 2002 + and BEES + impact assessment methods in SimaPro 7.3.3 to aid in the development of the LCAs.

Goal and scope

The goal of the LCA is to evaluate the environmental impact of the production of ethanol from sweet sorghum. The following three processing options were considered: 1) decentralized, 2) semi-centralized, and 3) centralized processing. The production of ethanol from sweet sorghum was also compared to the production of ethanol from corn. The functional unit that served as the basis of comparison was 1 MJ of anhydrous ethanol produced. The impact categories include: respiratory inorganics, terrestrial ecotoxicity, land occupation, GHG emissions, non-renewable energy use, and water intake. The impact categories were chosen with the aid of SimaPro's normalization tool, and the impact categories with larger significant impacts were chosen for this LCA. A summary of the chosen impact categories and a description are available in Table 2. This analysis only seeks to quantify the environmental impacts of the processes; it is not focused on the economics or the logistics.

System boundary

The Relative Mass Energy Economic (RMEE) is a system boundary selection method that uses mass, energy, and economic value to define the system boundary for LCAs. Defining rigorous system boundaries reduces subjectivity, increases repeatability, and minimizes unreliable results (Raynolds et al., 2000a). Because the selection of the system boundary affects the completeness of the LCA, the goal is to have a system boundary that includes all major environmental impacts. The general rule for excluding steps from an LCA study is that a step may be excluded only if doing so does not change the conclusions of the study (ISO, E., 14044: 2006, 2006; Raynolds et al., 2000a). It is difficult to prove that the exclusion of a step from a LCA study would not change the conclusions of a study. However, by using the RMEE methodology, a system boundary can be selected that excludes unit processes from the study without having to examine the entire system (Raynolds et al., 2000a) and in this comparative LCA, provides equivalent system boundaries.

The selection of the cut-off criteria (Z_{RMEE}), the ratio (mass, energy, economic value) of inputs to the final product, is crucial. Inputs that do not meet the cut-off are excluded from the system boundary and this contributes to uncertainty in the LCA results. For an input to be excluded, the mass, energy and economic ratio must be less than Z_{RMEE}. Statistical tests showed that as Z_{RMEE} increases, the 95% confidence interval also increases, therefore it is not recommended to use a Z_{RMEE} greater than 0.25 (ISO, E., 14040: 2006, 2006). The tests also show that Z_{RMEE} values from 0.05 to 0.25 have more than 90% of total environmental impacts likely to be inside the system boundary

Table 2
Impact category definitions and reference units.

Impact category	Description	Reference unit
Respiratory inorganics	Respiratory effect from the emission to air of inorganic particulate matter	kg of particulate matter
Land occupation	Occupied organic arable land	m^2 of arable land
Terrestrial ecotoxicity	Emissions to air, water, and soil that affect the ecotoxicity of soil	kg of triethylene glycol
GHG emissions	Emissions to air of greenhouse gases (ex. CO_2, CH_4, N_2O, CO)	kg of CO_2 eq.
Non-renewable energy use	Total primary energy use (Higher heating value)	MJ
Water intake	Water used during production	liters