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Life cycle greenhouse gas (GHG) impacts of a novel process for converting food waste to ethanol and co-products

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HIGHLIGHTS

- Co-fermentation using SSF at ambient temperature has potential as an ethanol pathway.
- Bio-refinery GHG emissions are similar to corn and MSW ethanol production processes.
- Net production GHG impact is negative with inclusion of waste disposal avoidance.
- Food waste diversion from landfills is the largest contributor to GHG benefits.

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ABSTRACT

Waste-to-ethanol conversion is a promising technology to provide renewable transportation fuel while mitigating feedstock risks and land use conflicts. It also has the potential to reduce environmental impacts from waste management such as greenhouse gas (GHG) emissions that contribute to climate change. This paper analyzes the life cycle GHG emissions associated with a novel process for the conversion of food processing waste into ethanol (EtOH) and the co-products of compost and animal feed. Data are based on a pilot plant co-fermenting retail food waste with a sugary industrial wastewater, using a simultaneous saccharification and fermentation (SSF) process at room temperature with a grinding pretreatment. The process produced 295 L EtOH/dry t feedstock. Lifecycle GHG emissions associated with the ethanol production process were 1458 gCO_2e/L EtOH. When the impact of avoided landfill emissions from diverting food waste to use as feedstock are considered, the process results in net negative GHG emissions and approximately 500% improvement relative to corn ethanol or gasoline production. This finding illustrates how feedstock and alternative waste disposal options have important implications in life cycle GHG results for waste-to-energy pathways.

1. Introduction

Renewable transportation fuels have the potential to mitigate climate change and contribute toward energy independence and security. However, current fuels based on sugar or starch energy crops face significant challenges in terms of economics, availability of feedstock, land use conflict and life cycle greenhouse gas (GHG) emissions. Using waste as a feedstock offers an alternative that avoids many of these problems while also addressing the growing challenge of waste management.

Food scraps account for 21% of waste currently reaching landfills in the United States [1]. In a landfill, food scraps decompose rapidly to produce methane, often before landfill gas (LFG) recovery systems are in place [2]. Landfills accounted for approximately 16% of total U.S. anthropogenic methane emissions in 2010 [1]. Alternatively, food waste can be broken down to simple carbohydrates and converted to ethanol in a bio-fermentation process. Using waste as a feedstock for ethanol production provides the service of waste disposal and has the potential to generate revenue

Abbreviations: ABV, alcohol by volume; CO_2, carbon dioxide; CH_4, methane; DDGS, dried distillers grains and solubles; EtOH, ethanol; FFS, Feed/Fuel Slurry; GHG, greenhouse gas; LCA, Life Cycle Assessment; LFG, landfill gas; t, metric tonne; MSW, municipal solid waste; N_2O, nitrous oxide; SSF, simultaneous saccharification and fermentation; ww, wastewater; WWT, wastewater treatment.

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to ethanol producers in the form of "tipping fees," which along with other valuable co-products can contribute to bio-refinery profitability.

Industrial (e.g. food processors) and retail (e.g. food preparation) wastes offer significant potential as a feedstock source because they can be source separated and are often a disposal burden to the generator. Fruit juice and cannery industrial waste have been reported as potential biofuel feedstocks [3,4]. Food scraps, which are generally more complex lignocellulosic materials, also have the potential for conversion to ethanol. However, these substrates require the breakdown of starch, cellulosic or hemicellulosic materials into monomeric sugars to enable fermentation. One method of achieving this is simultaneous saccharification and fermentation (SSF) in which enzymatic hydrolysis is performed together with fermentation; this offers the benefit of reduced inhibition of enzymatic activity by saccharification end products, as well as reduced investment costs [5,6]. Although, empirical studies have demonstrated the potential to create ethanol from food scraps using SSF [7–10], commercial-scale bioethanol plants utilizing food scraps do not yet exist. However, a National Renewable Energy Laboratory (NREL) model for lignocellulosic conversion based upon the SSF process has been used to analyze municipal solid waste (MSW) to ethanol conversion potential [11,12]. Implementation of SSF can vary, but most processes are optimized to include an acid or thermal pretreatment and operate at elevated temperatures. Furthermore, commercial models are usually on the scale of 40–80 million gallons of ethanol/year and often include some form of cogeneration to utilize waste heat [11].

Co-fermentation of feedstocks has received limited attention in the literature. Bellmer and Atieh [13] and Dwidar et al. [14] suggest that co-fermentation of beverage waste feedstock with other waste streams can improve pH, provide nutrients, and minimize diffusion of oxygen that might inhibit fermentation. Other studies have reported synergies when sugar- or starch-rich diluents were co-fermented with cellulosic feedstock (e.g., presaccharified wheat with wheat straw [15] or furfural residue with corn kernels [16]).

This study analyzes a pilot fermentation plant where lignocellulosic food scraps are combined with a sugar rich diluent. The food scraps are ground without any other pretreatment and simultaneously co-fermented with diluent, at ambient temperature. The process produces ethanol as well as compost and animal feed co-products; the business model also encompasses revenue for the service of waste disposal. Furthermore, fermentation and dehydration are conducted at separate facilities. This distributed model minimizes the infrastructure and regulatory requirements at smaller fermentation facilities located close to waste streams, while taking advantage of economies of scale by conducting dehydration at a centralized hub.

The objective of this study is to estimate and analyze the GHG impacts of this novel process. Pilot plant (1/15th scale) fermentation data are combined with small-scale commercial distillation data to create a model of the full ethanol production process. This model is used to assess the life cycle GHG impacts and to evaluate the potential of the process as an alternative fuel pathway. The results are compared to those of corn ethanol and conventional gasoline. This study is unique in the literature in that it analyzes a process that produces ethanol from industrial food waste, whereas existing literature analyzes processes for the conversion of MSW to ethanol [12,17,18]. Comparison of our results to these studies highlights the significant impact of waste feedstock composition which is discussed. Conclusions presented here are intended to contribute to knowledge in the areas of bioethanol production, waste management, and related policy.

2. Methods

2.1. Conversion process modeling

The process and system boundaries are shown in Fig. 1. The bio-refinery process is modeled using primary data from the pilot fermentation plant and a commercial dehydration plant and supplemented with data from the literature (represented by shaded blocks) where primary data were not available.

A mass balance was performed for a control run at a pilot scale fermentation plant (10 wet t/day) operated by Epiphergy LLC. The control run consisted of 4.7 wet t of feedstock: 2.3 wet t lignocellulosic feedstock, consisting of food scrap waste from a supermarket chain and 2.4 wet t of diluted fruit syrup food processing waste as a diluent. The source-separated feedstock was transported from the waste generators in totes on trucks. Upon receipt, the food scraps were ground without any other pretreatment and mixed with the diluent. The mixture was combined with cellulose and starch biocatalysts and antimicrobial agents and simultaneously fermented with *Saccharomyces cerevisiae* at ambient temperature. The resulting ferment slurry contained a dilute concentration of ethanol, residual solids, and yeast grown during fermentation. The solids were separated using an 80 μm filter and fed into a composting process, which is accelerated by the grinding and fermentation. The volume and ethanol content of the filtered ferment, and mass of compost produced were measured. These processes are represented by steps 1.1–1.4 of Fig. 1. In step 1.5 a portion of the dilute ferment is concentrated to create a Feed/Fuel Slurry (FFS) with 15% ABV. This is done to reduce transport weight as much as possible without requiring additional costs and regulatory burden associated with transport of flammable liquids. This process is modeled based on literature pertaining to small-scale ethanol distillation, assuming 0.22% ABV in the stillage [19]. Stillage wastewater volume, which is calculated by mass balance, was modeled to be processed onsite in a wastewater treatment (WWT) facility.

The FFS is transported to a regional facility where it is distilled to 96.5% (ABV) and dehydrated using a molecular sieve to anhydrous ethanol. Dissolved solids and solids that were not removed by the filtering process at the fermentation plant, are separated and dried to create an animal feed product similar to dried distillers grains and solubles (DDGS). Wastewater is treated in an onsite WWT facility. The ethanol dehydration process is estimated to be 96.5% efficient.

2.2. Life Cycle Assessment (LCA) methods

2.2.1. Goal and scope

The objective of the analysis is to evaluate this waste-to-ethanol process as an alternative biofuel pathway in terms of GHG emissions. A functional unit of 1 L of ethanol is used which is then converted to a unit of transport energy (1 MJ) for comparison to conventional gasoline (CG).

2.2.2. System boundaries

The bio-refinery system boundaries are shown as bolded lines in Fig. 1. It consists of two phases: fermentation and dehydration. The system boundary is set where the waste is introduced into the system. The food production processes that generate the waste are considered fixed with respect to process, materials, and consumption and thus not included within the boundaries [20,21].

The life cycle impacts include both indirect and direct emissions. These include, the indirect emissions associated with the production, transmission and distribution of electricity used in the process; the direct and upstream emissions from combustion of natural gas during phase 1 and phase 2 distillations; the