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Energy consumption and greenhouse gas emissions from enzyme and yeast manufacture for corn and cellulosic ethanol production

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Abstract Enzymes and yeast are important ingredients in the production of ethanol, yet the energy consumption and emissions associated with their production are often excluded from life-cycle analyses of ethanol. We provide new estimates for the energy consumed and greenhouse gases (GHGs) emitted during enzyme and yeast manufacture, including contributions from key ingredients such as starch, glucose, and molasses. We incorporated these data into Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model and observed that enzymes and yeast together contribute 1.4 and 27 % of farm-to-pump GHG emissions for corn and cellulosic ethanol, respectively. Over the course of the entire corn ethanol life cycle, yeast and enzymes contribute a negligible amount of GHG emissions, but increase GHG emissions from the cellulosic ethanol life cycle by 5.6 g CO_2e/MJ.

Keywords Enzymes · Ethanol · Life-cycle analysis · Yeast

Introduction

Yeast and enzymes play a key role in the conversion of corn starch, corn kernel fiber, and lignocellulosic feedstocks to ethanol. Enzymes are protein biocatalysts that prepare feedstocks for fermentation through processes such as liquefaction and saccharification. Yeast is a microorganism that ferments the resulting sugars to ethanol. Although alternatives to yeast are sought, especially for conversion of lignocellulosic feedstocks to ethanol (Dhutta et al. 2010), yeast remains the most common microorganism in the fermentation step.

To pursue sustainable biofuel production, life-cycle analysis (LCA) has been used to compare the energy and environmental effects of biofuels and baseline fossil fuels (Wang et al. 2011; Cherubini and Strømman 2011). In the supporting information for this paper (available online), Supplementary Figs. 1 and 2 depict the life-cycle stages of corn and cellulosic ethanol. With a few exceptions (Sheehan et al. 2004; MacLean and Spatari 2009), these two ingredients in the production of ethanol are often overlooked in the LCA of ethanol.

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In this paper, we incorporate new, manufacturer-provided energy consumption data for enzyme production, new industry data for enzyme and yeast dosages during ethanol production, and a new estimate of energy consumed during yeast production. Our analysis includes the contribution of key ingredients during enzyme and yeast production, such as glucose and molasses.

Production of enzymes and yeast

Enzymes

Ethanol plants generally purchase enzymes from outside suppliers, which typically manufacture enzymes via the submerged fermentation process (Nielsen et al. 2007). Starch ethanol production uses α-amylase (AA) and glucoamylase (GA) enzymes. Cellulosic ethanol production uses cellulase, which comprises endoglucanases, exoglucanases, and β-glucoside (Aden et al. 2002). Enzyme recycling, which would reduce the effective enzyme dosage, is currently not practiced. However, research efforts are under way to develop enzyme recycling technologies (Qi et al. 2012).

Yeast

Yeast, typically *Saccharomyces cerevisiae*, converts sugars in biomass into ethanol. While it is possible to grow yeast on-site at an ethanol plant, this approach, which requires sterile reaction media and equipment, can be costly and difficult (Knauf and Kraus 2006). Dry mill plants, which constitute approximately 90 % of US ethanol production facilities (Wang et al. 2011), generally purchase yeast from outside suppliers. It is uncommon for corn ethanol plants to recycle yeast for several reasons, as described in the supporting information. The yeast production process and the options for yeast product forms are also described in the supporting information.

Data sources and methodology

Two major enzyme producers provided energy and emissions data for this paper as we discuss in detail in the supporting information. Two enzyme users, the National Corn to Ethanol Research Center (NCERC) at Southern Illinois University and the Illinois River Energy (IRE) Ethanol Plant, shared enzyme dosage data.

Table 1 presents aggregated manufacturer data and values from MacLean and Spatari (2009) for enzyme dosages during ethanol production and for steam and electricity consumption during enzyme production. When total fossil fuel consumption from a data source was aggregated, we assumed that shares of electricity and steam were the same for each data source. We note that it is possible the manufacturers used co-product allocation to account for the production of a soil amendment from cell debris separated from the enzyme product (Nielsen et al. 2007), allocating total energy consumption at the enzyme production facility between the enzyme product and the soil amendment.

Yeast manufacturing material and energy flow data for the fuel ethanol industry are scarce. We therefore developed an estimate of energy and ingredient consumption during yeast production from a National Renewable Energy Laboratory (NREL) technical-economic analysis of lignocellulosic biomass conversion to ethanol via a biochemical process (Humbird et al. 2011), as described in the supporting information.

In our analysis, we use Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) (Argonne National Laboratory 2012) to model the life cycle of fuel ethanol (cellulosic and corn), including the impacts of yeast and enzymes. GREET parameters, including transport distances, are described in the supporting information.

Results

Figure 1 displays the contribution of ingredients and manufacturing to AA, GA, cellulase, and yeast. Production of GA consumes a good deal of electricity

Table 1 Enzyme dosage during ethanol production (kg enzyme/dry metric ton substrate) and energy consumption during enzyme production (MJ/kg enzyme)

Enzyme	Dosage (kg enzyme/dry metric ton substrate)		Steam (MJ/kg enzyme)		Electricity (MJ/kg enzyme)	
	I	M	I	M	I	M
α-amylase	0.36	0.8	4.0	4.9	7.0	10
Glucoamylase	0.61	1.1	10	21	32	66
Cellulase	10–100	9.2–9.6	1.8	7.9	4.0	17

I industrial producer composite, *M* MacLean and Spatari (2009)

and is the most energy intensive to produce of the three enzymes we examined. Although the contributions of starch and glucose to the energy intensity of GA production are appreciable (5.3 %), the manufacturing energy of GA dominates. Glucose contributes minimally to the energy intensity of AA production. In the case of cellulase, nutrients make up 72 % of enzyme production energy. Yeast is slightly less energy intensive than cellulase to produce; key ingredients contribute 39 % to its total energy intensity.

Figure 2a and b place the contribution of enzymes and yeast in the context of ethanol production from the farm to the pump. In the production of starch ethanol, enzymes and yeast contribute only 1.4 % to farm-to-pump greenhouse gas (GHG) emissions. This percentage jumps to 27 % for cellulosic ethanol from switchgrass (when co-products are not considered). Table 2 compares our results to those of MacLean and Spatari (2009). We estimate that GHG emissions due to enzyme use in the production of corn ethanol are roughly 75 % of that reported by MacLean and Spatari (2009). In the case of cellulosic ethanol, our GHG emissions contribution to total ethanol production is about 1.5 times that of MacLean and Spatari (2009). The larger value that we report stems from differences between the two studies in the identity, feed rates, and energy intensity of key ingredients in cellulase production. MacLean and Spatari (2009) did not include yeast in their analysis. Yeast production contributes just under 2 % of the ethanol farm-to-pump production GHG emissions in the case of cellulosic ethanol (again excluding the impact of co-products).

Figure 3 displays the life-cycle GHG emissions of ethanol (corn and cellulosic with a switchgrass feedstock), with and without the contributions of yeast and enzymes. The increase in net GHG emissions for corn ethanol is very small when contributions from enzymes and yeast manufacturing are included. In the case of cellulosic ethanol, an increase in 5.6 g CO_2e/MJ of life-cycle GHG emissions is observed.

In our analysis, we used the low end of a range of possible cellulase dosages in cellulosic ethanol production, as reported by enzyme manufacturers. If we adopt the midpoint (50 kg enzyme/dry metric ton substrate), the contribution of enzymes to life-cycle cellulosic ethanol GHG emissions increases by 17 g

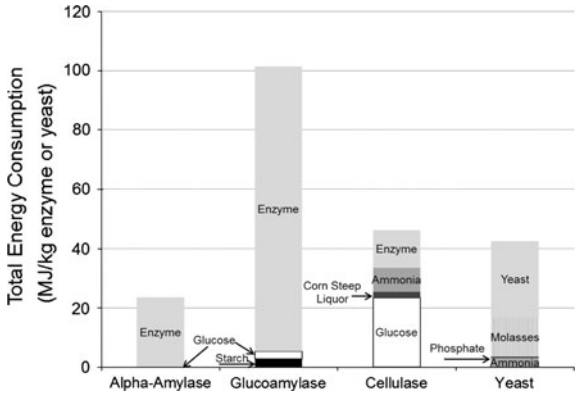

Fig. 1 Contribution of ingredients and manufacturing to the energy consumption (MJ/kg) during enzymes and yeast production (*Note* renewable energy contained in bio-derived compounds (e.g., corn starch) not included)

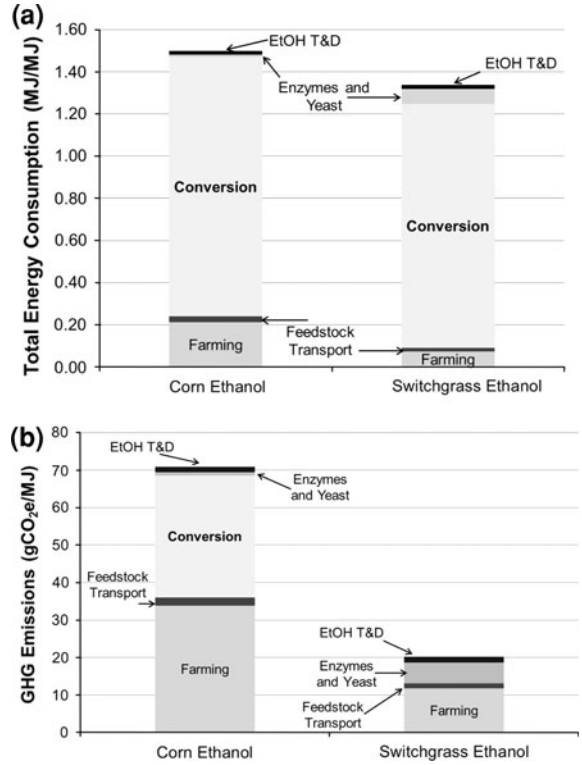

Fig. 2 **a** Total energy consumed during ethanol production (MJ/MJ ethanol) and **b** GHG emitted during ethanol production (g CO_2e/MJ ethanol) (*Note* co-products of corn ethanol (animal feed) and cellulosic ethanol (electricity) are not included. Renewable energy contained in bio-derived compounds (e.g., corn starch) not included in **a**. Corn and cellulosic ethanol co-products can provide GHG credits of −12 and −20 g CO_2e/MJ, respectively. Land-use change emissions and biogenic CO_2 emissions from the cellulosic ethanol plant are not included)

Table 2 Enzyme and yeast contributions to total GHG emissions in ethanol production (g/MJ ethanol)[a]

	Corn ethanol		Cellulosic ethanol from switchgrass	
	This study	MacLean and Spatari (2009)	This study	MacLean and Spatari (2009)
Enzymes	0.72	1.1	4.6	3.3–3.6[a]
Yeast	0.12	0	0.95	0
Total	0.84	1.1	5.6	3.3–3.6

[a] Conversion technologies are (1) ammonia fiber explosion followed by simultaneous saccharification (SSCF) and co-fermentation and (2) dilute acid pre-treatment followed by SSCF

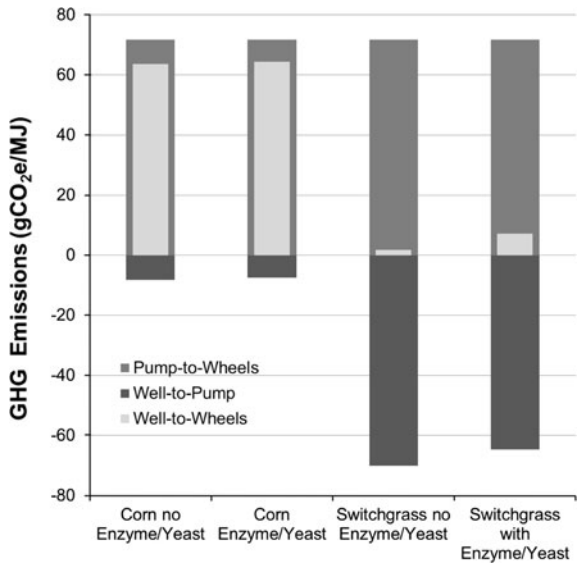

Fig. 3 Life-cycle GHG emissions of corn and switchgrass-derived ethanol with and without the contributions of enzymes and yeast (*Note* results for corn and cellulosic ethanol include GHG emissions from land-use change of 9.1 and 1.3 g CO_2e/MJ, respectively)

CO_2e/MJ. Alternatively, an optimistic scenario that reflects possible advances in cellulase technology could permit both the glucose feed rate to cellulase production and the cellulase feed to ethanol production to be halved. The subsequent contribution of yeast and enzymes to ethanol life-cycle GHG emissions drops from 5.6 to 2.7 g CO_2e/MJ. (Halving the glucose feed rate to cellulase production alone yields a GHG emissions contribution of 4.4 g CO_2e/MJ.) Similarly, if we assume that glucose consumption during corn ethanol enzyme production and the enzyme dosage during corn ethanol production are halved, the contribution of enzymes and yeast to corn ethanol GHG life-cycle emissions drops from 0.84 to 0.48 g CO_2e/MJ.

Conclusions

We report new data for purchased energy consumption and GHG emissions during the manufacture of AA, GA, and cellulase. These data are significantly below that of previous reports (MacLean and Spatari 2009). We also developed a new estimate of the energy consumed and GHGs emitted during yeast production. Through this effort, we incorporated enzymes and yeast in the GREET LCA for biofuels. Of the enzymes examined in this study, GA is the most energy-intensive enzyme to produce. Although cellulase is less energy intensive to produce than GA, the higher dosage of enzymes in the cellulosic ethanol process translates into a greater impact of enzymes on life-cycle GHG emissions and energy consumption for cellulosic ethanol than for corn ethanol. Ingredients in cellulase production contribute substantially to its energy intensity, and a better understanding of ingredient identities and consumption rates would improve estimates of this enzyme's impacts on cellulosic ethanol. Yeast is not an inconsequential contributor to ethanol's life-cycle impacts. Our study reiterates the importance of including the impact of yeast and enzymes in biofuel LCA, especially in the case of cellulosic ethanol, and highlights the need for additional information about the consumption of key ingredients during cellulase production. It is important to note that cellulase enzyme technology is rapidly advancing (Zhang et al. 2012), permitting lower doses of the enzyme in ethanol production. Frequent revisiting of cellulase dosage assumptions is therefore necessary.

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