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Corn Amylase: Improving the Efficiency and Environmental Footprint of Corn to Ethanol through Plant Biotechnology

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Treatment of starch-based grain with an alpha-amylase enzyme is essential to convert available starch to fermentable sugars in the production of ethanol. In an effort to improve the efficiencies of corn-based ethanol production, Syngenta has developed a new variety of corn that expresses alpha-amylase directly in the seed endosperm. This technology represents a novel approach to improving ethanol production in a way that can be integrated smoothly into the existing infrastructure. Between October 2007 and December 2008, Syngenta, in collaboration with Western Plains Energy, LLC, of Oakley, Kansas, conducted a commercial-scale trial of Corn Amylase. The results of this trial confirmed many of the potential benefits identified in laboratory trials, which include significant reductions in the amount of natural gas, electricity, water, and microbial alpha-amylase required to produce a gallon of ethanol. These savings are realized through the unique characteristics of Corn Amylase that enable ethanol producers to increase throughput at the plant without the typical tradeoff of losing conversion yield. Corn Amylase, therefore, will reduce the demand for natural resources, the consumption of fossil fuels, and the emission of greenhouse gases. Corn Amylase will also reduce utility costs at the plant and improve the energy balance (compared to ethanol produced from conventional corn).

Key words: alpha-amylase, corn, energy balance, ethanol, greenhouse gas, throughput, trial.

Introduction

Over the past 18 months, biofuels made from food crops such as corn have received considerable attention as to whether they provide environmental benefits greater than the petroleum-based fuels they are intended to replace. The net energy balance and carbon footprint are metrics that have been widely used to debate the viability of corn-based ethanol production. The energy balance for corn-based ethanol is calculated by dividing the energy value (BTU) in a gallon of ethanol by the fossil fuel energy used to produce that gallon of ethanol. Fossil fuel consumption includes all farming, transportation, and manufacturing activities. Depending on the methodology used, the net energy balance for corn to ethanol has been reported to be in the range from 0.54 to 2.10 (Wang, 2005).[1]

Researchers have also found varying results from analyzing the carbon footprint of corn-based ethanol. When compared with gasoline, ethanol from corn has been found to reduce greenhouse gas (GHG) emissions by as much as 60%, while others have reported that it may increase carbon emissions over gasoline by as much as 20% (Wang, 2005). Most recently, two articles published in *Science* (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Searchinger et al., 2008) raised the importance of considering land-use changes when evaluating greenhouse gas improvements.

While the ranges are broad, the life cycle analyses (LCA) published in *Science*—and referred to above—principally reflect the agricultural (feedstock) phase of biofuel production and do not account for the continuous improvement in efficiencies at the ethanol plant. The biofuel industry has made a number of advancements in energy and water efficiency and ethanol yields over the past several years (Wu, 2008). Corn Amylase (CA) represents another approach to improving upon the efficiency, cost, and environmental footprint of biofuels. Consequently, this article reviews the potential economic and environmental benefits of CA on the production of ethanol from corn and sorghum.

Methods

Syngenta has developed a corn variety that expresses a thermostable alpha-amylase enzyme within the grain. The corn-expressed enzyme has characteristics suitable for the starch processing step of dry-grind ethanol pro-

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[1] *A value less than 1.0 indicates a process that consumes more energy than it produces; a value greater than 1.0 indicates a process that produces more energy than it consumes.*

duction. Ideally amylases for this industry should work at high temperatures and have low calcium requirements. Syngenta's amylase enzyme expressed in Event 3272 (i.e., Corn Amylase) matches these criteria and is expected to replace the microbially produced alpha-amylase as an external input for ethanol production. Syngenta has concluded its consultation on the food and feed safety of amylase corn and is awaiting regulatory approval from the USDA. Syngenta has also applied for import clearances from a number of countries that purchase grain and distiller's grains from the United States, such as Japan, Mexico, and Canada.

From October 2007 through December 2008, Syngenta collaborated with Western Plains Energy, LLC (WPE) of Oakley, Kansas, to evaluate the processing characteristics of CA. WPE has a plant capacity of roughly 40 million gallons per year and uses a combined feedstock of corn and/or sorghum for ethanol production. Numerous experiments were performed during the 14 month of evaluation. The data presented here were collected during a 31-day trial conducted in August 2008.

WPE mixed CA corn with conventional corn and sorghum at various ratios to assess conversion rates and throughput. The trial results were then used to simulate the effects of CA on a typical dry-grind ethanol plant by using the USDA-Eastern Regional Research Center (ERRC) ethanol process model (Kwiatkowski, McAloon, Taylor, & Johnston, 2005) and an ethanol production cost model developed at LECG. The USDA-ERRC model was utilized to determine the impact of increasing the rate of throughput, which is accomplished primarily by increasing the solids content in fermentation. Cost implications of utility savings experienced during the trials were calculated through the LECG model.

The energy balance and greenhouse gas emission results described below are based upon the principal findings from the 31-day trial and simulations:

- Variable operational costs were reduced by about $0.04 per gallon.
- Microbial alpha-amylase was eliminated from the production process.
- Water use for fermentation was reduced by 5.8%, and total process water usage was reduced by 7.7%.
- Electricity use was reduced by 1.8% on a per gallon basis.
- Natural gas consumption was reduced by 8.9% on a per gallon basis.
- The solids content in the fermenter could be increased by 5%.

GREET Analysis

The impact of CA corn on GHG emissions was estimated using Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (GREET, 2008). While several scenarios were modeled to gain an understanding of the product's potential, three scenarios were identified as the best indicators of CA corn's impact, based on the trials. These three scenarios include: (1) a conventional corn baseline, (2) feedstock containing 25% CA with increased throughput,[2] and (3) feedstock containing 25% CA with increased throughput, in conjunction with Syngenta's recommended agronomic practices for no-till production (Syngenta unpublished data). The three scenarios help define (based on the timeframe the study was conducted) the potential benefits of CA corn and Syngenta's grower recommendations.

The Renewable Fuel Standard (RFS) established in the 2007 Energy Independence and Security Act specifies that the use of first-generation ethanol (mostly from corn) will reach its peak in 2015. For this reason, 2015 was selected as the base year for all modeling scenarios. A second notable parameter of the analysis is that the supply chain was shortened from the default GREET 'Well (farm) to Pump' analysis to a more appropriate 'Farm to Ethanol Plant' analysis. Rather than include the transportation, distribution, and storage of finished ethanol, this analysis encompasses all activities from the farm to the ethanol plant. This change reflects the realization that all differences between conventional No. 2 yellow corn and CA corn are captured through the production phase of ethanol. Extending the analysis to the fuel pump dilutes the overall impact of CA corn in reducing GHGs by including distribution impacts that are not unique to or affected by CA corn.

Baseline

The baseline scenario takes into account all activities and processes that contribute to the production of ethanol from corn at a dry-grind manufacturing facility. This includes all downstream energy use for agriculture as well as the discovery, extraction, processing, and transportation of necessary fossil fuels. The simulation was

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[2] *The final use rate of corn amylase has not been determined. The 25% ratio of CA to conventional feedstock was used for the purposes of this study only.*

run for the year 2015, assuming that dry-mill plants make up 88% of production (wet mill 12%), and 80% of dry-mill thermal energy is produced from natural gas (20% from coal). Several changes were made to the GREET version 1.8 model to reflect the most recent plant efficiency data as reported by May Wu of Argonne National Laboratory in March 2008. In addition, because alpha-amylase is not factored into GREET as an ethanol production input (M. Wu, personal communication, 2008), the LCA impact from the production and transportation of microbial alpha-amylase was added to the baseline. The alpha-amylase LCA reflects the impact of how alpha-amylase is sourced by WPE at their Oakley plant when CA corn is not used. Factors from GREET were used to calculate the impact of transporting the amylase from the supplier, and previous work by Nielsen, Oxenbøll, and Wenzel (2007) was used to capture the impact of producing microbial alpha-amylase.

Scenario 1

Scenario 1 simulates the replacement of 25% of a plant's conventional corn feedstock with CA corn and the increase of plant throughput by 6%. An increased solids/liquid ratio provided by CA decreases water use and will increase throughput. Throughput is a measure of the amount of corn that can be processed into ethanol during a production run. The ability to increase throughput provides the ethanol plant manager with a greater degree of flexibility. When using CA corn, the manager will have the ability to increase output by processing more corn than would be possible with conventional No. 2 yellow corn. Alternatively, the manager could reduce the plant's operating rate and still maintain the same quantity of ethanol as with conventional No. 2 yellow corn. A reduced operating rate would lower stress on machinery and equipment and potentially reduce repair and maintenance costs. A 6% increase in throughput is consistent with the anticipated reduction in water use and increase in solids during fermentation. The results highlight the operational impacts due to these changes, and the associated impact to energy balance and GHG emissions. Changes implemented in this scenario include:

- The elimination of the life cycle impacts associated with the production and transportation of microbial alpha-amylase.
- Reduction in electricity use by 1.8% and natural gas consumption by 8.9% on a per gallon basis.

Scenario 2

Scenario 2 includes all the changes from Scenario 1 as well as the impact of shifting from GREET's baseline agronomic practices—based on the US average of all tillage practices (M. Wu & M. Wang, personal communication)—to the Best Management Practice (BMP) recommendations of Syngenta for use on CA corn in the Midwest, which include no-till. Corn Amylase will be marketed—and is expected to be grown—in the Midwest Region where 10 states account for 83% of corn production and more than 90% of ethanol production. Therefore, projected corn yield and chemical input rates for the Midwest were selected for use in Scenario 2, in contrast to the national averages used in the baseline. No-till efficiencies were calculated from 2006 University of Illinois data, which compares typical tillage systems for corn operations with no-till systems (University of Illinois, 2006).

CA will be commercialized as a specialty grain and, thus, will be grown under contract by farmers within a closed-loop system. Participating farmers will be encouraged to implement sustainable agronomic practices, such as no-till and the use of cover crops, that will help increase soil carbon sequestration and nitrogen fixation and reduce fuel and fertilizer use. For example, the amylase trait will be stacked with those for herbicide tolerance, an enabler of no-till, as well as insect resistance to increase yield. Furthermore, Syngenta maintains an agricultural product portfolio of herbicides, pesticides, and fungicides that can enable CA growers to realize the highest yields with the lowest environmental impact possible. The grower contract will also ensure the ethanol plant receives a consistent and steady supply of quality CA grain.

It is important to note that the agronomic practices are not related directly to the properties of CA but reflect differences in input use (fertilizer and chemical application) and field practice recommendations of Syngenta relative to GREET defaults. When compared with GREET, Syngenta recommends lower application rates of nitrogen and insecticides and higher rates of P_20_5, K_20, and herbicides (Cirrus Partners, 2008). When this is considered, model changes due to agronomic recommendations include:

- the elimination of field tillage resulting in a 38% reduction in on-farm diesel fuel use,
- a reduction in insecticide use by 65%,
- a reduction of nitrogen use by 16%,
- an increase in herbicide use by 19%, and

- an increase in the use of P_20_5 by 11% and K_2O by 20%.

The increases in herbicide and fertilizer use are more than offset by reductions in other inputs and savings gained from adjusted field practices. Therefore, Syngenta's agronomic recommendations have a significant beneficial impact.

GREET Results

Energy Balance

Scenario 1 reflects the energy savings realized from replacing 25% of a plant's conventional corn feedstock with CA corn, and Scenario 2 adds the net impacts of reduced fertilizer, pesticide, and diesel fuel use proscribed by Syngenta's agronomic BMP. The replacement of 25% of a plant's corn requirements with CA corn results in a 6.6% improvement in energy balance on a per-gallon basis when compared to the use of conventional corn. The improvement in energy balance under this scenario is provided by a combination of reduced electricity and natural gas use and the elimination of the life cycle impacts associated with the production and transportation of microbial alpha-amylase. When the Syngenta BMP agronomic recommendations (Scenario 2) are included, the net energy balance improves by 10.7% per gallon compared to the baseline.

The use of CA corn also results in substantial reductions in greenhouse gas emissions. The replacement of 25% of a plant's corn requirements with CA corn (Scenario 1) is shown to result in a reduction of nearly ½ pound of CO_2-equivalent per gallon of ethanol, or 4.9%. Of the three gases that are classified as having global warming potential, carbon dioxide has far and away the greatest impact on GHG emissions. The GREET model results indicate that the use of CA corn will reduce CO_2 emissions by nearly 6%. The incorporation of Syngenta's BMP agronomics with the replacement of 25% of a plant's corn requirements with CA corn reduces total GHG emissions by 1.06 pounds of CO_2-equivalent per gallon of ethanol, or 11%, relative to baseline levels. The results of this analysis are summarized in Table 1.

Table 1. GREET results of Corn Amylase simulations.

	Baseline No CA	Scenario 1 25% CA	Scenario 2 25% CA plus BMP[1] agronomics
Energy balance	1.657	1.766	1.835
% change from base		6.6%	10.7%
Total GHG (lbs CO_2 equivalent)	9.64	9.17	8.58
% change from base		-4.9%	-11.0%
CH_4	0.39	0.36	0.36
N_2O	1.78	1.77	1.43
CO_2	7.47	7.03	6.79

[1] *Syngenta Best Management Practices*

Other Benefits

Reduced Water Use

The use of CA can reduce the amount of water required to produce a gallon of ethanol by 7.7%. This reduction is directly related to the 5% increase in solids content during fermentation.[3] If CA achieves a 30% market share of US dry-grind plants by 2015, the 7.7% reduction would save 870 million gallons of water annually, which would provide every man, woman, and child in the United States with an additional 45, 8-ounce glasses of water per year or two glasses of water for each of the world's 6.8 billion people.

Reduced Electricity Requirements

Trial results reveal that on average, an ethanol plant with the capacity to produce 100 million gallons per year (MGY) would reduce electricity use by 1.3 million kilowatt-hours (kWh) and save $84,000 by using CA corn. Using US Department of Energy's Energy Information Administration (US DOE EIA) data on household electricity use as a base, if Event 3272 corn achieves a 30% market share by 2015, this reduction is equivalent to 51.2 million kWh of electricity, or enough power to light more than 54,000 homes for a full year (US DOE, EIA, n.d.).

Reduced Natural Gas Use

Typically, natural gas is the second largest component of production cost for an ethanol producer. Syngenta trial results show that increased throughput capabilities gained from using CA corn can reduce natural gas use on a per-gallon basis by 8.9% for the period of time tested. Based on these results, a 100 MGY plant using CA corn could reduce its annual natural gas consump-

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3. *A 7.7% reduction in water use is the result of modeling a 5% increase in solids content in the fermenter, using the USDA-ERRC ethanol process model.*

tion by approximately 244 billion BTUs, at a savings of about $1.6 million per year. If CA corn achieves a 30% market share by 2015, this translates into a savings of approximately 9.6 quadrillion BTUs and nearly $61 million. This quantity of natural gas would be sufficient to heat more than 175,000 homes for an entire year (US DOE EIA, 2008, Table 1).

Table 2. Impact of a potential 2% yield increase from CA corn.

	Baseline No CA	CA 2% yield increase	CA 2% yield + BMP[1]
Energy balance	1.657	1.772	1.839
% change from base		6.9%	11.0%
Total GHG (lbs CO_2 equivalent)	9.64	9.11	8.54
% change from base		-5.4%	-11.4%
CH_4	0.39	0.36	0.36
N_2O	1.78	1.75	1.42
CO_2	7.47	7.00	6.77

[1] *Syngenta Best Management Practices*

Potential for Increased Ethanol Yields

While CA trials have shown improvements in energy balance and GHG emissions due to throughput efficiencies, preliminary evaluations conducted by Syngenta in a pilot-scale laboratory and at WPE indicate that Event 3272 corn also may provide an improvement in starch conversion that could result in higher ethanol yields. The opportunity for an ethanol plant manager to manage production for improved ethanol yield could reduce the amount of corn required to produce a given amount of ethanol. Table 2 illustrates the potential energy and GHG impact of an assumed modest 2% increase in ethanol yields when combined with the throughput benefits defined above.

The replacement of 25% of a plant's corn requirements with CA corn would result in a 6.9% improvement in energy balance when compared to the use of conventional corn if CA corn provided a 2% ethanol yield increase. When the Syngenta BMP agronomic recommendations (Scenario 2) are included, the net energy balance would improve by 11%, compared to the baseline.

Improved ethanol yields also would result in substantial reductions in greenhouse gas emissions. The replacement of 25% of a plant's corn requirements with CA corn that provided a 2% yield improvement would reduce GHG emissions on a CO_2-equivalent per-gallon basis of 5.4%. The incorporation of Syngenta's BMP agronomics with the replacement of 25% of a plant's corn requirements with CA corn would reduce total GHG emissions by 1.1 pounds of CO_2-equivalent per gallon of ethanol for a 2% yield improvement. An improvement in ethanol yields means that an ethanol plant would require fewer bushels of corn to produce the same amount of ethanol. If CA corn provided a 2% ethanol yield improvement at a 30% market share, the corn requirement could be reduced by 27.6 million bushels at the 2007 average yield of 151 bu/acre or the equivalent of 166,500 acres (US Department of Agriculture, National Agricultural Statistics Service, 2009).

It is important to note that the potential for ethanol yield increases from CA corn are preliminary and must be validated by additional plant trials.

Conclusions

Over the past 18 months, corn ethanol has received a lot of attention and has been blamed for increases in the cost of oil (Johnson, 2008), food, and grain (Mitchell, 2008); food shortages, riots, and trade restrictions (Martin, 2008); land-use changes in developing nations (Searchinger et al., 2008); the loss of biodiversity in the Amazon (Keeney & Nanninga, 2008); and increases in global warming (Fargione et al., 2008). It is well recognized that a number of other issues have contributed to these events—not least of which is the rise in oil and fuel prices to record levels—increased meat consumption, drought, investor speculation, etc. Nonetheless, the results seen with CA indicate the potential for technology to help ameliorate many concerns with the use of renewable fuels.

For example, critics of corn ethanol state that the corn-ethanol production process delivers little improvement in energy balance and a 10-13% improvement in GHG emissions when compared with gasoline. The Energy Independence and Security Act of 2007 stipulates that renewable fuels produced at new facilities must lead to at least a 20% reduction in lifecycle GHG emissions compared to GHG emissions generated by petroleum products replaced by ethanol (Energy Independence and Security Act, 2007). The use of CA in conjunction with recommended agronomic practices brings corn-based ethanol over that 20% hurdle, which is critical for the renewable fuel industry.

Further opportunities for improvements in energy balance and GHG emissions will likely be identified as more experience is gained with CA. Improvements such as these would prove valuable to financially challenged ethanol plants, farmers, and technology providers. Regardless, it's clear that technology will play a critical role in making current biofuels more efficient and second generation biofuels a commercial reality.

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