Chapter 2

Ethanol Production and its Co-Products

Dry-Grind and Wet Milling Processes

Introduction

This chapter described the basic principles of ethanol production in order to provide a better understanding of the nutritional characteristics and feeding value of the corn co-products produced by the fuel ethanol industry.

Conversion of Glucose to Ethanol

In the U.S., corn is the predominant source of starch (glucose) used to produce ethanol. With the exception of sugar cane, corn provides the highest ethanol yields compared to any other feedstock being used (**Table 2**). However, research is underway to develop methods to convert carbohydrates from cellulosic feedstocks such as softwood (Arwa et al., 2005), non-starch polysaccharides (Arthur, 2006), as well as using sugar beets (Savvides et al., 2000) to glucose for use in producing ethanol. The nutrient composition of the feedstock used to produce ethanol determines the nutrient profile of the distiller's co-products produced.

Table 2. Starch content and ethanol yield of various feedstocks.

Feedstock	Moisture (%)	Starch (%)	Ethanol Yield (L/MT)
Starch	-	100.0	720
Sugar cane	-	-	654
Barley	9.7	67.1	399
Corn	13.8	71.8	408
Oats	10.9	44.7	262
Wheat	10.9	63.8	375

Source: Saskatchewan Agriculture and Food (1993).

The energetic efficiency of converting glucose to ethanol is about 51.4%, while 48.6% is attributed to the production of carbon dioxide. The efficiency of producing ethanol from moisture-free starch is about 56.7%.

Dry-grind Ethanol Production

Particle size reduction of grain

As shown in **Figure 3**, the initial step in ethanol production using dry-grind technology is to reduce the particle size of corn by grinding it with a hammer mill. Hammer mills crush the corn grain by high speed, rotating hammer tips. The fineness of the ground corn is determined mainly by the rotor volume, hammer tip speed, number of hammers, and the screen opening size (Dupin et al., 1997). The screens used in the hammermill are normally in the range of 3 to 5 mm in diameter. Particle size of the grain can affect ethanol yield (Kelsall and Lyons, 1999), and therefore, ethanol producers tend to use finely ground corn to maximize ethanol yield. As shown in **Table 3**, an extra 0.20 gallons (0.85 liters) of ethanol can be produced if the corn is ground through a 5mm screen compared to an 8 mm screen.

Table 3. Ethanol yield from ground corn of different particle size.[1]

Particle Size	Ethanol Yield (gallons/bushel)
Fine grind corn, 5 mm screen	2.65
Coarse grind corn, 8 mm screen	2.45

[1] Kelsall and Lyons, 1999.

Cooking and saccharification

Water and recycled stillage are added to the ground corn, which act as conditioners to begin leaching of soluble protein, sugars, and non-starch bound lipids (Chen et al. 1999). Cooking is then used to hydrolyze starch into glucose along with the addition of amylolytic enzymes in order for yeast (*Saccharomyces cerevisiae*) to convert glucose to ethanol. Temperatures typically used during the cooking process are 40-60°C in the pre-mixing tank, 90-165°C for cooking, and 60°C for liquefaction (Kelsall and Lyons, 1999). Gelatinization of starch starts to occur between 50 and 70°C. A critical step in converting starch to glucose involves the completeness of starch gelatinization (Lin and Tanaka, 2006). During gelatinization, nearly all of the amylose in the starch granules is leached out (Han and Hamaker, 2001), which increases viscosity due to swollen granules and gels consisting of solubilized amylose (Hermansson and Kidman, 1995).

Complete hydrolysis of the starch polymer requires a combination of enzymes. Amylases are the most widely used, thermostable enzymes in the starch industry (Sarikaya et al., 2000).

These include α-amylases or glucoamylase (Poonam and Dalel, 1995). Enzymes must be thermostable in order for starch hydrolysis to occur immediately after gelatinization. Enzyme use accounts for about 10-20% of the ethanol production cost (Gregg et al., 1998).

Some ethanol plants use batch cooking systems whereas others use continuous cooking systems (Kelsall and Lyons, 1999). In a batch cooking system, a known quantity of corn meal is mixed with a known quantity of water and recycled stillage. In the continuous cooking process, corn meal, water, and recycled stillage are continuously added into a premix tank. The temperature of the premix tank is maintained just below that needed for gelatinization, and the mash is continuously pumped through a jet cooker. The temperature of the cooker is set at 120°C. From the cooker, the mash passes into the top of a vertical column, and moves down the column in about 20 minutes, it is then passed into a flash chamber for liquefaction at 80-90°C. High temperature-tolerant amylase is added at 0.05-0.08% w/w cereal to bring about liquefaction. The retention time in the liquefaction/flash chamber is about 30 minutes. The pH of the system is controlled to be within 6.0-6.5. Batch systems use less enzymes compared to continuous systems and are also more energy efficient. The main disadvantage of batch systems is reduced productivity or feedstock utilization per unit of time.

Fermentation

Fermentation is the process where yeast convert sugars to alcohol. The most commonly used yeast is *Saccharomyces cerevisiae* (Pretorius, 2000) because it can produce ethanol to a concentration as high as 18% in the fermentation broth. *Saccharomyces* is also generally recognized as safe (GRAS) as a food additive for human consumption (Lin and Tanaka, 2006). In ideal fermentation, about 95% of sugar is converted to ethanol and carbon dioxide, 1% is converted into cellular matter of the yeast cells, and 4% is converted into other products such as glycerol (Boulton et al., 1996). Yeast use accounts for about 10% of the ethanol production cost (Wingren et al., 2003).

Pre-fermentation is used to achieve the desired number of yeast cells for fermentation and is a process that involves agitation for 10-12 hours to achieve 300 to 500 million cells/ml. Fermentation takes place at a temperature of about 33°C (Thomas et al., 1996), at a pH of about 4.0 (Neish and Blackwood, 1951), and lasts between 48-72 hours (Ingledew, 1998). In addition to ethanol, carbon dioxide is produced and can either be collected or is released into the air.

The control of normal yeast growth is a key factor in efficient ethanol production. The activity of the yeasts is highly dependent on the temperature of the fermentation system. Torija et al. (2003) reported that the optimum temperature for reproduction and fermentation in yeast is 28 and 32°C, respectively. Fermentation efficiency of S. *cerevisiae* at high temperatures (above 35°C) is low (Banat et al., 1998). Therefore, a cooling mechanism is required in fermentation systems.

One challenge of managing fermenters in an ethanol plant is preventing contamination with other microbes. Microbial contamination causes reduced ethanol yield and ethanol plant productivity (Barbour and Priest, 1988). The most common organisms associated with microbial contamination are lactobacilli and wild yeasts. These microbes compete with *Saccharomyces cerevisiae* for nutrients (trace minerals, vitamins, glucose, and free amino nitrogen) and produce inhibitory end-products such as acetic and/or lactic acid. *Dekkera/Brettanomyces* wild yeasts have become a concern in fuel alcohol production (Abbott and Ingledew, 2005). A reduction in lactic acid bacterial contamination is currently achieved by using antibiotics in fuel ethanol plants (Narendranath and Power, 2005).

Distillation of ethanol

After fermentation, ethanol is collected using distillation columns. Ethanol collected from the fermenters is contaminated with water, and is purified using a molecular sieve system to remove the water and produce pure ethanol.

Corn oil extraction

Crude corn oil can be produced at corn ethanol plants by extracting the oil from the thin stillage portion of the DDGS production process (CEPA, 2011). Corn oil extraction from thin stillage occurs after fermentation and distillation, and before the drying to produce DDGS. Corn oil extraction systems have been added to existing ethanol plants to increase the energy efficiency of the plant as well as increase the total amount of fuel that is produced per metric tonne of corn processed. The installation of corn oil extraction equipment in an existing ethanol plant facilitates the production of a biodiesel feedstock without affecting ethanol production volumes. Different corn oil extraction technologies are available commercially to the ethanol industry.

Most of the ethanol industry is using a “Step 1” extraction process where corn oil is extracted from thin stillage after it is removed from the whole stillage using centrifugation (CEPA, 2011). The resulting partially concentrated thin stillage is heated and the corn oil is extracted by a second centrifuge. Heat exchangers use steam to raise the temperature of the thin stillage to facilitate extraction, so that after corn oil is extracted, thermal energy from the stillage is recovered in heat exchangers to heat the incoming stillage.

Thin stillage contains approximately 30% of the oil available in the corn, of which most can be recovered using this “Step 1” process, depending on individual ethanol plant conditions (CEPA, 2011). In general, a typical ethanol plant uses corn that contains approximately 4% corn oil (weight basis) which ends up in DDGS if oil extraction is not used. For example, a dry-grind ethanol plant with an annual production capacity of 190 million liters can recover 5.7 million liters of corn oil per year.

The “Step 2” process has not yet been implemented in most U.S. ethanol plants, but is an additional extraction process that can capture an additional 30% of the corn oil that is bound in the whole stillage prior to the centrifuge separation of the wet grains and thin stillage (CEPA, 2011). Since more than 40% of the total oil in corn is trapped within the wet cake, the wet cake is “washed” to liberate this oil so that it can be extracted in the “Step 1” system. The additional oil made available to the “Step 1” extraction process generally doubles the production of corn oil. Therefore, the combination of using both “Step 1” and “Step 2” processes, 60 to 70% of the corn oil present in the distiller’s co-products can be extracted. As a result, these technologies allow the extraction of 23 to 27 liters of corn oil for every 380 liters of ethanol produced.

For every 3.8 liters of ethanol produced, 2.4 kg of DDGS is produced without the use of corn oil extraction (CEPA, 2011). However, with corn oil extraction, DDGS yield is reduced by approximately 0.06 kg per liter of ethanol produced, representing a 9.4% reduction in DDGS yield. Removal of corn oil affects the nutritional profile of the DDGS, primarily by reducing the fat and energy content, and increasing the protein concentration. For some food animal species such as swine, poultry, and fish, high fat and energy content of DDGS is very important, whereas dairy and beef cattle can use the reduced-oil DDGS more effectively. Refer to **Chapters 15, 18, 20, and 22** for more information about the effects of feeding reduced-oil DDGS to beef cattle, dairy cattle, poultry, and swine, respectively.

Co-product production

The water and solids remaining after distillation of ethanol are called whole stillage. Whole stillage is comprised primarily of water, fiber, protein, and fat. This mixture is centrifuged to separate coarse solids from liquid. The liquid, called thin stillage, goes through an evaporator to remove additional moisture resulting in condensed distiller's solubles (syrup) which contains approximately 30% dry matter. Condensed distillers solubles can be sold locally to cattle feeders or combined with the coarse solids fraction and dried to produce dried distiller's grains with solubles. The coarse solids are also called wet cake and contain about 35% dry matter. Wet cake can be sold to local cattle feeders without drying, dried to produce dried distiller's grains, or mixed with condensed distiller's solubles and dried to produce distillers dried grains with solubles (88% dry matter).

Wet Milling

Unlike dry-grind ethanol plants that ferment the entire ground corn kernel, wet mills separate the corn kernel into various fractions, which allows for the production of multiple food and industrial products including ethanol. The corn wet milling industry was developed in the early 19^{th} century with the primary purpose of producing starch for use in food and laundry products (Kerr, 1950). In the 1920's wet mills began producing crystalline dextrose (Newkirk, 1923), and after World War II, began producing ethanol. In the early 1990's, wet mills began producing high fructose corn syrup in addition to other products. A majority of wet mill plants have been built in the last few decades (Johnson and May, 2003). An overview of the wet milling process is shown in **Figure 4**.

Grain cleaning

Corn is initially cleaned to remove broken kernels, chaff, pieces of cobs, and foreign material. This process is important because broken kernels can release starch in steep water, which can gelatinize leading to undesirable viscosity during evaporation of steep water into steep liquor (May, 1987).

Steeping

Steeping involves soaking of the corn kernels under the controlled temperature (48-50°C), time (35-50 hours), concentration of SO_2 (0.1-0.2%), and lactic acid (Watson, 1984). Water acts as a conditioner so that milling can be performed under optimal conditions (Bass, 1988). Steeping aids in softening the corn kernel for milling, inhibits microbial growth, and enhances pure starch recovery (Bartling, 1940).

Milling

After soaking, the corn germ becomes soft and rubbery. Hydrocyclones with counter rotating discs and intermeshing fingers tear apart the corn kernels and separate the germ (May, 1987). Since the germ is lighter in weight than the rest of corn kernel it can be easily separated by centrifugal force. Once removed, the germ is purified to remove starch and protein extracts by washing with water. Oil is then extracted from the germ to produce corn oil.

Fiber is separated by pumping the slurry (starch, gluten, fiber, and kernel fragments) with considerable force on 120° wedge-wire screen. Fiber particles are large in shape and are screened out to leave starch and protein.

Gluten is separated by high speed centrifuges due to the fact that protein is lighter in weight compared to starch (May, 1987). Gluten is then thickened in centrifuges, dewatered to contain 42% solids by vacuum filtration, and dried to 88% solids for sale as corn gluten meal (Jackson and Shandera, 1995).

Starch processing

Impurities, in the form of proteins, are removed by washing the starch in fresh water using a countercurrent process in the centrifuges. The purified starch contains less than 0.4% protein with less than 0.01% free protein (May, 1987). The protein that is removed consists primarily of starch-protein complexes that are recycled back to the primary separation step. Purified starch can then be dried, fermented to produce ethanol, or refined to produce corn syrup. The procedure used to produce ethanol from starch in wet mills is similar to that previously described for dry-grind ethanol plants.

Co-product production

Corn steep liquor is a high-energy liquid feed ingredient. It contains about 25% crude protein on a 50% dry matter basis. This product is sometimes combined with corn gluten feed, or may be sold separately as a liquid protein source for beef or dairy rations. It also can be used as a pellet binder and is a source of B-vitamins and minerals.

Corn germ meal contains 20% protein, 2% fat, and 9.5% fiber. It has an amino acid balance that makes it valuable in poultry and swine diets.

Corn gluten feed is a medium protein ingredient composed of the bran and fibrous portions of the corn kernel. It may, or may not, contain the condensed corn extractives. This by-product can be sold as a wet or dry feed ingredient. The bran and condensed extractives (sometimes called germ meal) are combined and dried in a rotary dryer. The dried corn gluten feed is made into pellets to facilitate handling. It typically contains about 21% protein, 2.5% fat, and 8% fiber. Wet corn gluten feed (45% dry matter) is perishable in 6-10 days and must be fed within that time period or stored in an anaerobic environment. Corn gluten feed is primarily used in dairy and beef cattle rations.

Corn gluten meal is a high protein concentrate, which typically contains 60% protein, 2.5% fat, and 1% fiber. It is a valuable source of methionine. Corn gluten meal also has a high level of xanthophylls, which makes it an attractive ingredient in poultry diets as a source of yellow pigment.

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