CHAPTER 3

Dry-Grind Production of Ethanol, Distillers Corn Oil and Corn Co-Products

Introduction

THE UNITED STATES IS A GLOBAL LEADER IN BIOFUELS PRODUCTION (ethanol and biodiesel), which is a result of high agricultural productivity and infrastructure, along with government directives to use biofuels for reducing dependence on fossil fuels and greenhouse gas emissions. The U.S. production of ethanol has continued to increase over the past decade, with over 59 billion liters expected to be produced in 2017 (**Figure 1**; Renewable Fuels Association, 2017) using over 5.5 billion bushels of corn. About 90 percent of U.S. ethanol production occurs in 214 dry grind ethanol plants in 29 states (**Figure 2**; RFA, 2017). As a result, about 36.5 million metric tons of distillers co-products (**Figure 3**; RFA, 2017) and 1.5 billion kg of distillers corn oil are expected to be produced in 2017 **(Figure 4**; RFA, 2017). Today, wet mills comprise only about 10 percent of U.S. ethanol production, and produce a relatively low proportion of corn co-products, with only 3.6 million metric tons of corn gluten feed, and about 705,000 metric tons of corn gluten meal (**Figure 5**; RFA, 2017). Of the 36.5 million metric tons of distillers co-products produced, about 11 million metric tons are exported **(Figure 6**; RFA, 2017), with 70 percent used in beef, dairy, swine and poultry feeds in the U.S. (**Figure 7**; RFA, 2017). Use of DDGS in swine and poultry diets has been increasing since 2004 (**Figure 8**; RFA, 2017), but beef cattle consume about 45 percent of domestic wet and dry corn co-products, followed by dairy cattle (31 percent), swine (15 percent) and poultry (8 percent).

Beginning in 2005, a few U.S. ethanol plants began extracting some of the corn oil from thin stillage before producing reduced-oil DDGS. The primary incentive for doing this was the relatively low capital investment and cost of operation, which resulted in a rapid return on investment and increased ethanol plant revenue from producing and marketing another co-product. Currently, about 51 percent of distillers corn oil is used in animal feeds (i.e. poultry and swine), 45 percent is used for biodiesel production, and the remaining five percent is used for other industrial purposes (**Figure 9**; RFA, 2017). As of 2017, exports of distillers corn oil have been minimal, but it is an excellent and economical energy source that should be seriously considered for use as a high-energy feed supplement by feed manufacturers in the export market.

The primary feedstocks used to produce biodiesel around the world are rapeseed, soybean and palm oil (IEA, 2015), but the use of animal fats and recycled cooking oil has been increasing in recent years (Licht, 2013). Soybean oil has been the lowest cost feedstock for biodiesel production in the U.S., but there are incentives to use lower cost alternatives, such as distillers corn oil, to meet future biodiesel production goals at reduced costs, while minimizing competition with edible lipids used for human consumption. The triacylglycerol content of fats and oils can serve as a partial replacement for petroleum in diesel engines once these lipids undergo transesterification, which is a chemical process used to convert fatty acids from glycerol esters to acyl esters (e.g. methyl, ethyl). This conversion is needed because the high viscosities of triacylglycerols result in poor atomization in diesel engine cylinders leading to inefficient combustion, fuel deposition, engine wear, and failure (Ziejewski et al., 1986a,b; Goering et al., 1987).

The purpose of this chapter is to describe the basic principles of ethanol production, corn oil extraction and DDGS production to have a better understanding of the nutritional characteristics and feeding value of the corn co-products produced by the U.S. fuel ethanol industry.

Figure 1. Historic U.S. Fuel Ethanol Production

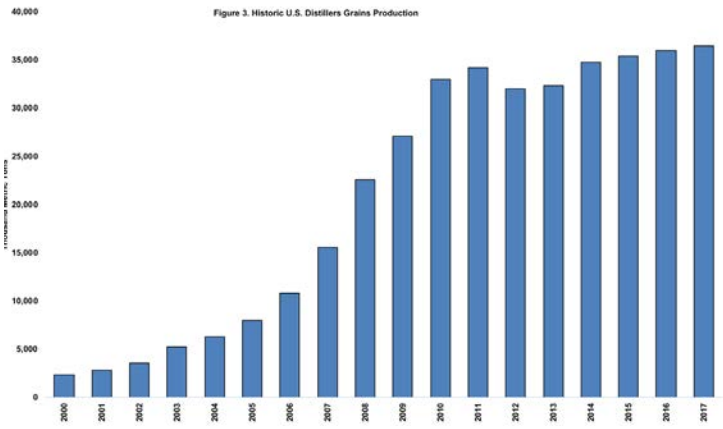


Figure 2. Ethanol Production by Technlogy Types

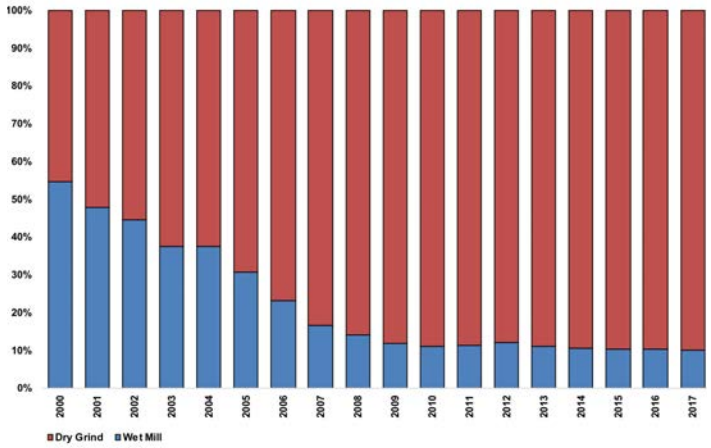


Figure 3. Historic U.S. Distillers Grains Production

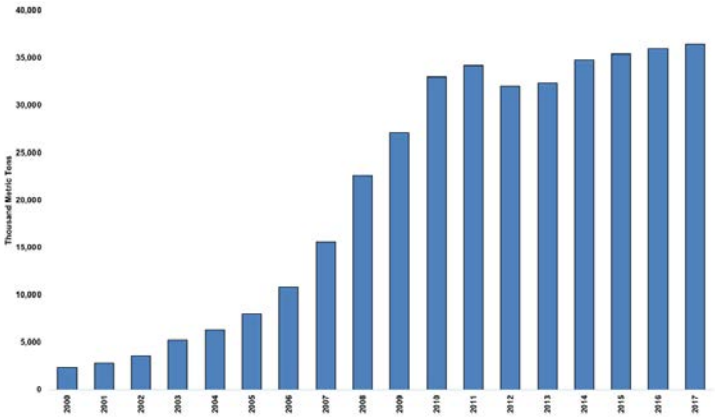


Figure 4. Historic U.S. Corn Distillers Oil Production

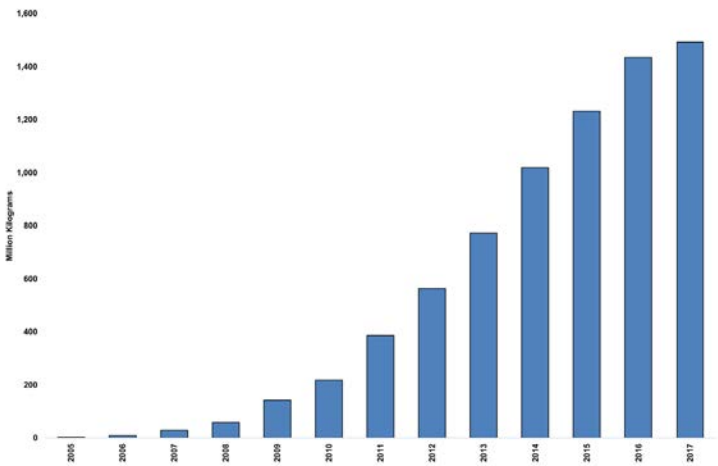


Figure 5. U.S. Fuel Ethanol Co-products Production

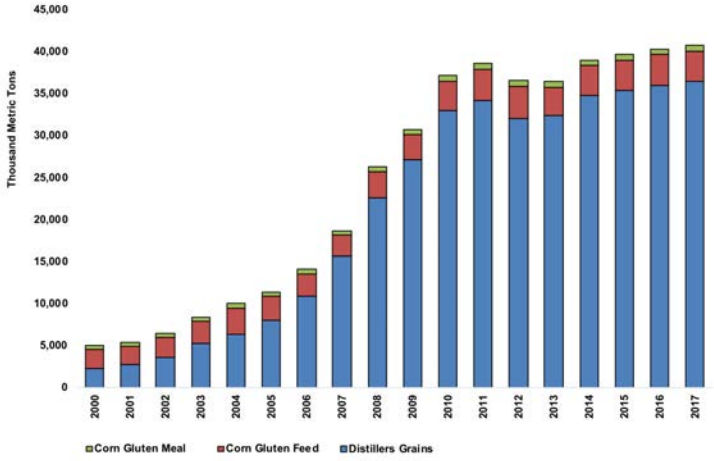


Figure 6. Historic U.S. Distillers Grains Exports

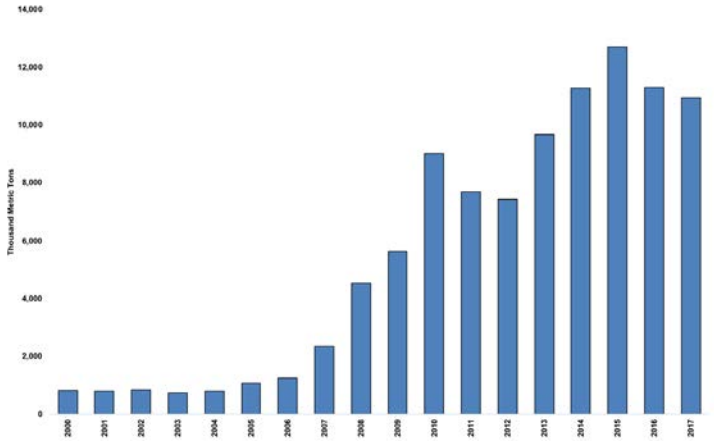


Figure 7. Export and Domestic Use of U.S. Distillers Grains

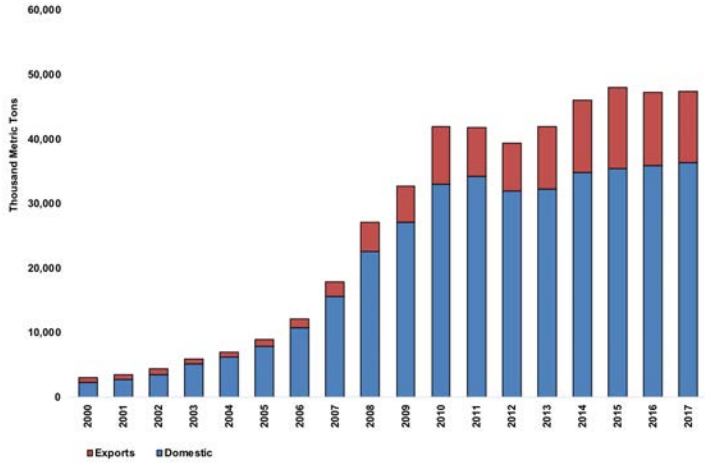


Figure 8. U.S. Distillers Grains Consumption by Species

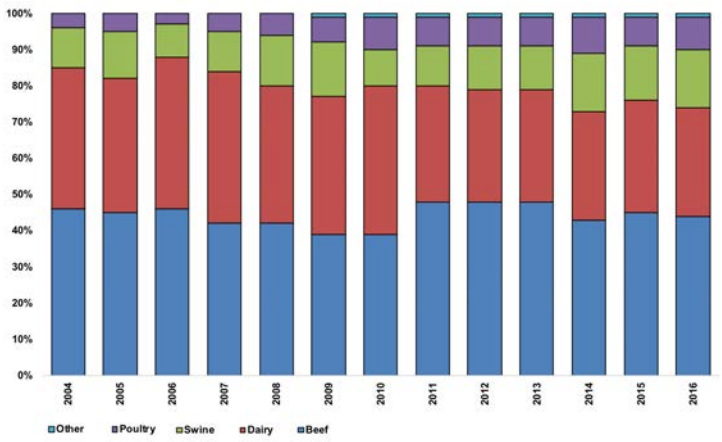
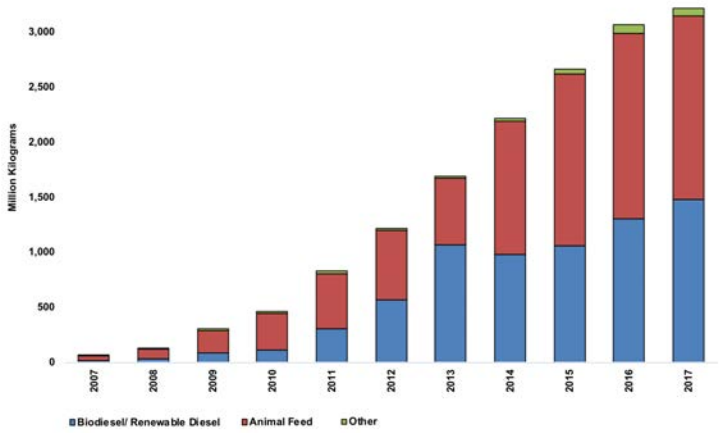


Figure 9. U.S. Corn Distillers Oil Use



Conversion of Starch to Ethanol

In the U.S., corn is the predominant source of starch (glucose) used to produce ethanol. With the exception of Sugarcane, corn provides the greatest ethanol yields compared to any other feedstock being used (**Table 1**). However, technologies have been recently developed to convert corn fiber and other cellulosic feedstocks to glucose for use in producing ethanol. The energetic efficiency of converting glucose to ethanol is about 51.4 percent, while 48.6 percent is attributed to the production of carbon dioxide. The efficiency of producing ethanol from moisture-free starch is about 56.7 percent. The nutrient composition of the feedstock used to produce ethanol determines the nutrient profile of the distiller's co-products produced.

Table 1. Starch content and ethanoal yield of various feedstocks (adapted from Saskatchewan Agriculture and Food, 1993)

Feedstock	Moisture (%)	Starch (%)	Ethanol Yield (L/MT)
Starch	-	100.0	720
Sugarcane	-	-	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

Dry-grind Ethanol Production

Particle size reduction of grain

As shown in **Figure 10**, the initial step in ethanol production using dry-grind technology is to reduce the particle size of corn by grinding it with a hammermill. Hammermills 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 2**, an extra 0.20 gallons (0.85 liters) of ethanol can be produced if the corn is ground through a 5 mm screen compared to an 8 mm screen.

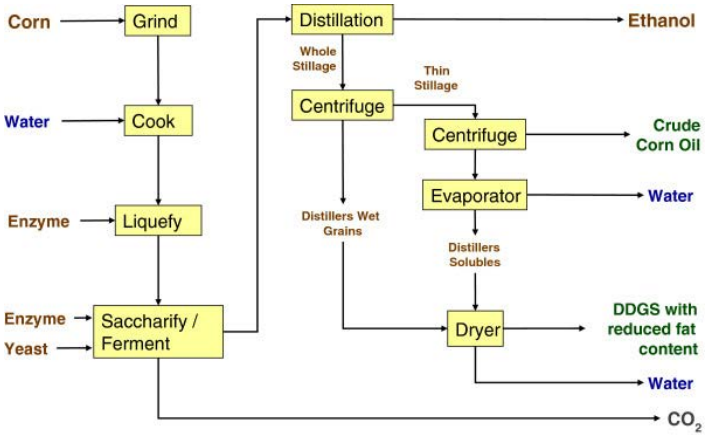


Figure 10. Dry-grind ethanol and co-product production process

Table 2. Ethanol yield from ground corn of different particle size (adapted from Kelsall and Lyons, 1999).

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

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 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 Kidry matteran, 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 for starch hydrolysis to occur immediately after gelatinization. Enzyme use accounts for about 10-20 percent 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 percent 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 fewer 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 percent 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 percent of sugar is converted to ethanol and carbon dioxide, one percent is converted into cellular matter of the yeast cells, and four percent is converted into other products such as glycerol (Boultonet al., 1996). Yeast use accounts for about 10 percent 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 yeast is highly dependent on the temperature of the fermentation system. Torija et al. (2003) reported 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 of the challenges 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

Although the majority (over 90 percent) of U.S. ethanol plants are using various oil extraction technologies to remove varying amounts of oil before producing DDGS, additional distillers corn oil extraction may occur in the future because the remaining ethanol plants not currently extracting corn oil may adopt this technology, and new technologies have been developed and are being implemented to extract additional oil in ethanol plants currently extracting corn oil. 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 produced per metric ton 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. Several commercial proprietary processes are used to extract corn oil from thin stillage after distillation of ethanol. Most of the ethanol industry is using a process where corn oil is extracted from thin stillage after it is removed from the whole stillage using centrifugation (CEPA, 2011). Thin stillage contains approximately 30 percent of the oil available in the corn, and 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. In general, these processes involve using various configurations of decanters, centrifuges, and heat to physically separate 30 to 70 percent of the oil in this co-product stream. All of the distillers corn oil produced through these processes is not suitable for human food use. However, solvent (hexane) extraction is routinely used to extract corn oil from corn germ to produce high quality corn oil for human consumption in wet mills (Moreau, 2005). Hexane extraction is very effective in capturing 90 percent of the corn oil in DDGS, but the high capital investment costs for constructing a hexane extraction facility has limited the adoption of this technology in the ethanol industry. Currently, only one facility (Novita, Brookings, SD) is using hexane extraction to remove corn oil from DDGS. This facility produces feed grade corn oil and a low-oil (3.5 percent crude fat) DDGS.

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, which represents a 9.4 percent reduction. Removal of corn oil affects the nutritional profile of the DDGS, primarily by reducing the crude fat content, with variable effects on energy and protein content. Refer to **Chapters 13, 15, 17, 18, 20, 21, 24, and 25** for more information about the effects of feeding reduced-oil DDGS to various animal species.

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 oil. This mixture is centrifuged to separate coarse solids from liquid. The liquid, called thin stillage, is subjected to an additional centrifugation step to extract oil before going through an evaporator to remove additional moisture to produce condensed distiller's solubles (syrup), which contains about 30 percent dry matter. Condensed distillers solubles (CDS) can be sold locally to cattle feeders or combined with the coarse solids fraction and dried to produce dried distiller's grains with solubles (DDGS). The coarse solids, also called wet cake, contain about 35 percent dry matter and 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 DDGS (88 percent dry matter). The proportion of various types of co-products produced by dry grind ethanol plants is shown in **Figure 11**.

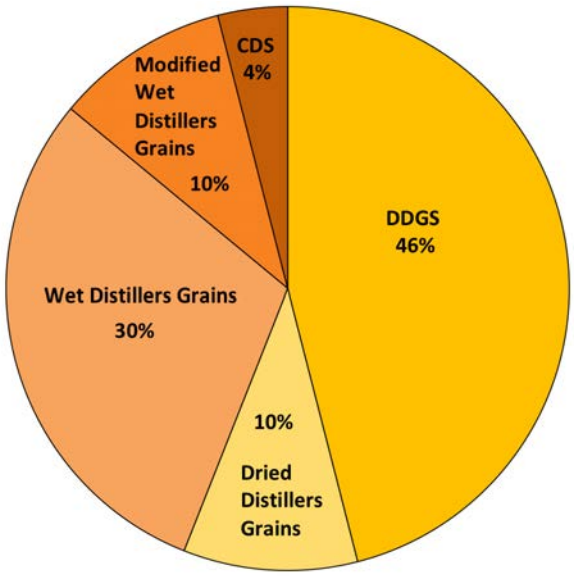


Figure 11. Proportion of various types of co-products produced in dry grind ethanol production (RFA, 2017)

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