Manufacturing of fuel ethanol and distillers grains—Current and evolving processes

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Before examining all of the different possible uses of distillers dried grains with solubles (DDGS), a discussion regarding ethanol and DDGS production methods is warranted. This chapter will cover current production processes and some of the new practices that have been developed and are being adopted at plants, including front-end fractionation and back-end fractionation. Additionally, standard coproduct definitions will be discussed, as they govern the marketing and sales of these materials.

## 5.1 PRODUCTION PROCESSES AND PRODUCTS

While corn can be converted into ethanol by three commercial processes, namely wet milling, dry milling, and dry grind ethanol processing (Rausch and Belyea, 2006), only the last process, which constitutes the major growth in the U.S. fuel ethanol industry in recent years, will be thoroughly discussed in this chapter. As pointed out in a previous chapter, over 80% of U.S. ethanol plants currently use the dry grind process. Some plants are, however, beginning to implement dry milling and wet milling fractionation processes to produce more product streams at less cost than a wet milling facility (RFA, 2009).

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5.1.1 **Dry Grind Processing of Corn to Ethanol**

The dry grind process has become the predominant method for production of fuel ethanol in recent years (in 2009 approximately 80% of all U.S. ethanol plants were dry grind) because of its lower investment and operational requirements, as well as advances in fermentation technology. The dry grind process (Figure 5.1) entails several key steps, including grain receiving, distribution, storage, cleaning, grinding, cooking, liquefaction, saccharification, fermentation, distillation, ethanol storage and loadout, centrifugation, coproduct drying, coproduct storage, and loadout. Additional systems that play key roles include energy/heat recovery, waste management, grain aeration, CO₂ scrubbing and extraction, dust control, facility sanitation, instrumentation and controls, and sampling and inspection. Figure 5.2 depicts an example of how all of these pieces may fit together in a commercial plant. During operation of a plant, there are many complex interactions between all of these components, and they all must work in concert for the plant to be efficient and effective.

A brief summary of dry grind ethanol production will be provided below. Additional detailed information on these processing steps can be found in Tibelius (1996), Weigel et al. (1997), Dien et al. (2003), Jaques et al. (2003), Bothast and Schlicher (2005), Rausch and Belyea (2006), and Ingledew et al. (2009). The reader is referred to these sources for more specific information. In addition, the effects of processing methods on physical properties are covered in Chapter 7, while the effects on DDGS composition are covered in Chapter 8.

While there are some “standard” configurations in terms of plant construction, each facility is actually unique—no two are identical. Design choices often depend upon individual client needs and requirements, operational flexibility, the ability to expand in the future, the creativity and imagination of engineers and designers, but most importantly, on cost.

5.1.1.1 **Receiving, Cleaning, and Storage**

As in traditional grain elevators, receiving operations introduce incoming grain into the storage facility. Corn is typically delivered to an ethanol plant in large wagons, hopper-bottom semitrucks, or even by rail cars at the large plants. The incoming grain is sampled at the receiving station (generally at or prior to the truck scale), and tested for moisture content, broken and foreign material, mold damage, and sometimes mycotoxin levels. Because of the extra expense associated with mycotoxin testing, plant managers typically monitor the harvest crop quality forecasts for mold and mycotoxin pressures, in order to determine how rigorous their mycotoxin testing should be. After testing, the inbound grain is then dumped into an underground receiving pit, and then transferred to mechanical distribution equipment (i.e., bucket elevators, spouts, and conveyors), which then transport the grain to storage. A key consideration with this operation is to maximize material throughput and minimize waiting time (especially at harvest). Receiving hopper (Figure 5.3) volumes can be up to 1200 bu (42.3 m³), and conveyor capacities are often greater than 20,000 bu/h (705 m³/h). Bucket elevators are used for vertical grain transfers (Figure 5.4), while drag or belt conveyors are used for horizontal transfers (although screw conveyors are often used for moving DDGS and distillers wet grains (DWG), but that will be discussed later).

In terms of grain storage, there are two options that are commonly used in the ethanol industry: concrete silos and steel bins (Figures 5.4 and 5.5). Concrete silos are most common for large-volume storage, and can be built with heights up to 150 ft (45.7 m), diameters up to 100 ft (30.5 m), and often have storage capacities of several hundred thousand bu (sometimes even greater than 1 million bu [35,239 m³]; ~28,000 tons; ~25,400 t) per silo. Steel bins, on the other hand, are more common for lower-volume storage (these are often found at small to midsize ethanol plants [~20 to 60 million gal/yr]), and are often used for future facility expansions (even at the large ethanol plants [~80 to 150 million gal/yr]). They are typically built with heights up to 115 ft (35 m), diameters up to 105 ft (32 m), and often have storage capacities more than 100,000 bu (3524 m³) (depending upon the diameter and height used). A typical rule of thumb is to have between 7 and 10 days of corn storage onsite at the ethanol plant.
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FIGURE 5.1 Flow chart of typical corn dry grind fuel ethanol and coproducts processing. (Adapted from Rosentrater, K. A. International Sugar Journal 109(1301): 1–12, 2007.)
FIGURE 5.2 General plan view of a typical fuel ethanol plant.

FIGURE 5.3 A below-ground grain receiving hopper accepts incoming corn by truck or rail, and then the corn is transferred to a bucket elevator by a drag conveyor (author's photograph).
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Figure 5.4 Corn is conveyed vertically by bucket elevators, and horizontally by drag conveyors. Note the drag scalper between the bucket elevator discharge and the distribution conveyor—it is used to clean the incoming grain. This is a 21-million gal/y plant (author's photograph).

Figure 5.5 A large-scale ethanol plant often uses both types of grain storage options. Large concrete silos are generally constructed with the original facility, and steel bins are then installed during future expansions. Note the small concrete silos used for DDGS storage. This is a 120-million gal/y (450 million L/y) plant (author's photograph).

After storage, the corn is then sent through at least one coarse cleaning operation, such as scalping and/or screening (Figure 5.6). This is done to remove broken corn kernels, fines, and chaff from the grain (i.e., screening), as well as foreign material (such as rocks, stems, cobs, leaves, and insects) (i.e., scalping). Also, large magnets (generally mounted on the grain spouts) are used to remove metal objects that may be in the grain stream. Removing these types of materials is very important for subsequent grinding and fermentation operations.
5.1.1.2 Grinding
In the conventional dry grind process, the entire corn kernel is ground into either a coarse meal or flour using either a hammer mill or a roller mill (Figure 5.7). Corn is ground before processing into ethanol in order to reduce particle size, which increases the surface area and thus exposes the starch in the endosperm so that it can more easily be accessed and transformed by the enzymes and yeast during subsequent processing steps. The resulting particle size can be affected by a number of factors, including the grinding equipment used (i.e., hammer mill or roller mill), the screen size (if a hammer mill is used), the roller or rotor speed, equipment wear, and the characteristics of the corn kernels themselves, such as hardness, shape, size, moisture content, existing stress cracks and fractures, and structural susceptibility to breakage. Typical particle size distributions of ground corn for ethanol production can range (lognormally) from 2.0 mm to less than 0.25 mm. Liu (2009a) found geometric mean diameter ($d_{50}$) values for ground corn ranging from 0.430 to 0.516 mm from six ethanol plants; while Rausch et al. (2005) found a geometric mean value of 0.94 from nine ground
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corn samples. Particle size has been shown to affect ethanol production. For example, Naidu et al. (2007) examined the effects of five ground corn particle size distributions (0.5, 2.0, 3.0, 4.0, and 5.0 mm). They found that particle size affected both ethanol yield and the concentration of soluble solids in the resulting thin stillage. The highest ethanol yield (12.6 mL/100 mL of beer) was attained at a particle size of 0.5 mm, which resulted in a soluble solids concentration of 25.1 g/L in the thin stillage. This was higher than the concentrations obtained for the other particle sizes, which had a mean concentration of 16.2 g/L.

Of the two main types of grinding systems, hammer mills are most common at ethanol plants because of high throughput capacities; but the trade off is high energy consumption (up to 600 hp [450 kW] can be required). Knives within the rotor assembly often travel at linear speeds between 9000 and 24,000 ft/min (2743 to 7315 m/min), depending on the diameter, and screen surface areas can be up to 6000 in² (3.9 m²), especially for the larger hammer mills.

Roller mills are not often used in ethanol plants, but they are sometimes used in plants that use the dry milling process (which will be discussed later). These types of mills often have higher capital costs than hammer mills, but they will have greater throughput at a given horsepower. They generally produce coarser, but more uniform particle size distributions, and will not generate as many fines, nor will they heat the product as much. Rollers are generally between 9 and 12 in (23 and 30.5 cm) in diameter, and often travel at linear speeds between 1500 and 3000 ft/min (457 and 914 m/min). The grooved rollers rotate at slightly different speeds in order to grind the kernels. Additional details on corn milling can be found in Kelsall and Piggot (2009).

5.1.1.3 Cooking and Liquefaction

After grinding, the corn flour is mixed with water from the backset and process condensate (10% to 60% of the total liquid supplied, in fact, thus conserving water and energy) to form a slurry of approximately 30% solids. The starch, which has been exposed during milling, is then prepared for fermentation. The pH is adjusted to between 5.5 and 6.0 by the addition of ammonia (NH₃), lime (CaCO₃), or sulfuric acid (H₂SO₄), and the enzyme α-amylase is added at a rate between 0.04% and 0.08% (of the corn, on a dry basis, db). The slurry is then heated to between 80°C (176°F) and 95°C (203°F) for 15 to 20 min (although some plants may hold the slurry as long as 40 min) to begin starch gelatinization, which makes the starch more accessible and amenable to modification during subsequent processing steps, and allows the slurry to be pumped because the viscosity is reduced. The ground corn, backset, and cook water can also be added together simultaneously, which can result in an immediate temperature of ~85°C (185°F). The slurry is cooked using a jet cooker, which injects steam into the slurry (Figure 5.8). An actuator is used to adjust the mixing of the streams, and cooking temperatures between 120°C (248°F) and 140°C (284°F) are achieved.

![Jet cooker diagram](image)

FIGURE 5.8  Schematic representation of a jet cooker.
During cooking, the slurry is held in a cooking column for 5 to 20 min, which fully gelatinizes the starch and breaks down the crystalline structure of the starch granules. After cooking, the slurry is then cooled to between 80°C (176°F) and 95°C (203°F) by flashing to atmospheric pressure in a vacuum condenser.

The mixture is then held in a liquefaction tank at 85°C (185°F) to 95°C (203°F) for 30 to 120 min, and more α-amylase enzyme is added at a rate between 0.05% and 0.08% (of the dry solids in the slurry). Caustic solution from the clean-in-place (CIP) system, or sulfuric acid, may be added to maintain the pH between 5.5 and 6.5. Lime and calcium may be added as nutrients for enzymes; backset may be added (generally 10% to 15%) for nutrients as well; and urea is often added as a subsequent nitrogen source (the yeast will require this nutrition during fermentation). The liquefaction step breaks the long starch polymers into short chains: the α-amylase enzyme hydrolyzes the starch polymers into short glucose chains called maltodextrins. A detailed discussion regarding enzymes, their importance to ethanol production, and their impact on DDGS is provided in Chapter 24.

5.1.1.4 Saccharification and Fermentation

The next step, saccharification, breaks down the short glucose chains into individual glucose molecules (known as dextrose). The enzyme α-amylase is used to cleave the α-1,4 glucosidic linkages, while the gluco-amylase is used to hydrolyze the α-1,6 glucosidic bonds (Ingledew et al., 2009). To accomplish this, mash from the liquefaction stage is cooled using plate heat exchangers to between 55°C (131°F) and 65°C (149°F). Another enzyme, gluco-amylase, is added either in its own tank or when the slurry is pumped to the fermentation vessels. Sulfuric acid is generally added to produce a pH between 4.0 and 4.5, which is optimal for this enzyme. The mash is kept at an elevated temperature for several minutes and then cooled to approximately 30°C (86°F) before being transferred into the fermentation tanks. In recent years it has become common for the saccharification step to occur in the fermentation tanks; this is known as simultaneous saccharification and fermentation (or SSF), and is indicated in Figure 5.1.

The mash is then transferred to fermentation tanks (Figure 5.9), which can have volumes greater than 2.0 million L (528,000 gal) each. Residence times in the fermentors may range from 40 to 72 h.

FIGURE 5.9 Fermentation tanks at a 120 million gal/yr (450 million L/yr) plant (author's photograph).
Generally speaking, pH levels are set at an initial pH of 4.0 to 5.0, and then they are allowed to run; sometimes they are maintained between 3.5 and 4.0. Temperatures are maintained at approximately 28°C (82°F) to 34°C (93°F) using external recirculating plate heat exchangers. In the fermentation vessels, gluco-amy lase may be added; this enzyme converts the remaining dextrins into glucose. Yeast (Saccharomyces cerevisiae) is also added to the mash to consume simple sugars and convert glucose molecules into heat, ethanol, and carbon dioxide. Theoretically, 1 g of glucose will yield 0.51 g of ethanol and 0.49 g of carbon dioxide, following:

\[ C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \]

These maximums, however, will be reduced in reality (generally 90% to 95% of theoretical) due to a number of factors, including the growth of yeast biomass cells (between 5% and 10% of the glucose may actually be consumed for cell growth) during fermentation, as well as the possible production of other secondary products, including glycerol, acetic acid, lactic acid, propanol, butanol, furfural, or other unintended products. Furthermore, protease activities must be monitored during fermentation to ensure that the yeast are receiving adequate nutrition. When complete, the fermentation slurry will contain between 10% and 15% ethanol, as well as yeast cells, nonfermentable materials (i.e., proteins, fibers, oils, minerals) that are processed further and sold as distillers grains, secondary products, and water. A common rule of thumb states that for each 1 kg of corn processed, approximately 1/3 kg of each of ethanol, carbon dioxide, and distillers grains will be produced. Another rule of thumb states that each bushel of corn (~56 lb; 25.4 kg) will yield up to 2.9 gal (11.0 L) of ethanol, approximately 18 lb (8.2 kg) of distillers grains, and nearly 18 lb (8.2 kg) of carbon dioxide.

The carbon dioxide that is produced during fermentation is cleaned, and most often released to the atmosphere. Sometimes it is compressed and sold to beverage manufacturers, but plant location, logistics, and economics often make this option cost prohibitive for most plants. Generally, the carbon dioxide is subjected to a wet scrubbing system, in which the gas stream is thoroughly in contact with water in order to remove volatile organic compounds (VOCs). The water from the scrubber is then recycled through the ethanol plant as process water.

5.1.1.5 Distillation, Dehydration, and Ethanol Storage
The fermented liquid stream that leaves the fermentors is known as beer. The beer is transferred to a large holding tank called the beer well. The beer is then sent through a stripping/rectifier column to remove the ethanol. The overflow from the column is a mixture of ethanol and water, while the underflow is a liquid stream called whole stillage—it contains all the nonfermentable components of the corn as well as the yeast cells and water. The ethanol–water mixture is further processed through distillation columns and molecular sieves to remove the water. The mixture is continuously pumped through a heated multiple-column distillation system (often with 28 to 34 separate stages) that boils off the ethanol (ethanol has a boiling point of 78°C (172°F), whereas water has a boiling point of 100°C (212°F)). The superheated alcohol vapor, which is approximately 190 proof (95% pure ethanol and 5% water) then moves on to dehydration in a molecular sieve (with one or more columnar beds), which physically separates the remaining water from the ethanol vapor. Molecular sieves contain microporous beads (such as zeolite), which adsorb the water vapor and result in 200 proof (100% pure) ethanol. The pure ethanol vapor is then condensed, cooled, blended with a denaturant (generally gasoline, so that it is not fit for human consumption, and thus not subject to beverage alcohol taxation) to produce the final liquid fuel ethanol product. This is then stored in tanks until it is loaded onto rail tanker cars for shipping to an ethanol/gasoline blending facility.

5.1.1.6 Coproduct Processing, Handling, and Storage
Conversion of nonfermentable residues into valuable animal feeds and other value-added coproducts is an important goal. The sale of all types of distillers products as livestock feed substantially
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contributes to the economic viability of ethanol manufacturing, and coproducts are thus vital components to each plant’s operation (Rosentrater, 2006). Conversion of nonfermentable materials into coproducts begins with the whole stillage. The whole stillage (which contains the nonfermentable materials, in both dissolved and suspended form) generally has an overall solids content of approximately 5% to 15%, and can be processed into a range of distillers grains coproduct feed materials (Figure 5.1), depending upon the specific configuration of the ethanol plant. The whole stillage is centrifuged (most commonly with a decanter style or solid-bowl centrifuge) to remove water (the resulting process stream is known as thin stillage, and contains high concentrations of the water-soluble solids); the dewatered product, on the other hand, is known as wet cake, and it contains the suspended solids that were removed from the whole stillage. Wet cake is often sold directly as DWG to cattle feedlots that are within the locality of the ethanol plant. Wet cake, or DWG, can contain between 35% and 50% solids (although it often has 50% to 65%), and thus is still very high in moisture. Sometimes syrup or partially dried DDGS is mixed with the DWG to produce a modified product. More details about processing these coproduct streams can be found in Meredith (2003).

Often between 10% and 50% of the thin stillage (which generally contains between 5% and 10% solids content) is recycled through the process; this is known as “backset.” The balance of the thin stillage is then processed through a multiple-effect evaporator system to produce condensed distillers solubles (CDS); this is referred to as “syrup” in the industry. During the evaporation process, the solids content of the thin stillage is increased to between 25% and 55%. CDS is a golden brown, thickened, highly viscous liquid. CDS is sold as a specific coproduct at only a few plants in the United States, and is usually fed to cattle as a mixed feed with silage. At most plants, it is recombined with the DWG, and this combination is then dried to about 10%–12% wet basis (wb), or over 90% solids content (to ensure a stable shelf life), to produce DDGS. This coproduct is a granular, bulk material, and is physically similar to other dry feed ingredients, such as soybean meal.

If the CDS is not added before the DWG is dried, then the resulting feed product is known as distillers dried grains (DDG). The majority of ethanol plants are set up to solely produce the dried coproducts (most currently produce DDGS, while only a few produce DDG). Dried products are stable, and can be either used locally or shipped via truck or rail for use by distant customers. Lately, however, there has been growing interest in local use of DWG, because it appears to offer some nutritional benefits to livestock, and the production of DWG substantially reduces the overall energy requirements for the ethanol plant vis-à-vis the production of DDG or DDGS.

Drying is one of the most energy-intensive operations of the ethanol plant, and can consume up to 1/3 of the plant’s entire energy supply (Meredith, 2003a, 2003b). As a rule of thumb, approximately 0.06 kg of natural gas is required to evaporate 1 kg of water (or 1000 BTU per 1 lb of water) during drying. Two main types of drying systems are used in U.S. fuel ethanol plants: rotary drum dryers (Figure 5.10) and ring dryers (Figure 5.11). Each of these types of systems has several potential configurations. For example, both the rotary drum and the ring dryers can have partial or full combustion gas recycling systems, and both can be constructed with either a direct-fired heat source, or they can be indirectly fired (i.e., use heat exchangers to heat the drying air). Additionally, rotary dryers can use steam tube heating as a heat source instead of air. The equipment used and manner in which the DDGS is dried will greatly impact the resulting nutritional quality as well as physical properties (more about the influence of processing conditions will be discussed in Chapters 7 and 8).

At this point in time, rotary drying is the predominant type of drying system used in U.S. ethanol plants (Figure 5.10 shows a generic schematic for this process); for larger plants, usually more than one high-capacity dryer operates simultaneously in parallel. To begin the drying process, two product streams (DWG and CDS) are blended in a mixing chamber, screw conveyor, or paddle mixer, before being conveyed to the dryer. Additionally, a portion of freshly dried DDGS (at approximately 10% moisture content) from the rotary drum dryer is mixed in as well (this DDGS is actually recycled through the system again). The ratio of DWG, CDS, and freshly dried DDGS is such that the solids content of the blend is about 65% before entering the dryer. Air temperatures in the
Products are thus vital fermentable materials into the whole stillage is centrifuged to remove water (the concentrations of the water-vat cake, and it contains the nonfermentable solids content of approximations coproduct feed materials at most plants, it is recom-

The balance of the thin produce condensed distillation the evaporation process, 5%. CDS is a golden brown, at only a few plants in the dryer are very high: at the dryer inlet the temperature can be over 500°C (932°F), and at the dryer discharge over 100°C (212°F). Most rotary dryers operate in a cocurrent configuration, that is, the product and the airflow move in the same longitudinal direction inside the dryer. Upon exiting the dryer, the DDGS will generally be slightly lower (nearly 10°) in temperature than the air discharge temperature, and it will have approximately 10% to 12% moisture content (wb). Between 50% and 70% of the dried DDGS is then conveyed to storage. The other (i.e., recycled) portion is routed back to the mixer where it is blended with incoming DWG and CDS. Residence times in rotary dryers can range from approximately 10 to 20 min (although some particles can reside as long as 60 min, depending upon the moisture).

It is inside the rotary drum dryer that the DDGS particles are formed, as the drying air removes water vapor and the particles are mixed with other drying particles. The resulting DDGS characteristics will thus depend upon a number of drying parameters: the ratio of DWG to CDS in the blend prior to entering the dryer, the process configuration used for blending (i.e., where in the process and how are the products blended), the ratio of recycled DDGS to stored DDGS, and drying parameters (such as drying temperatures, air flow rates, and drum rotation speed). Kingsly et al. (2010) examined the influence of some of these drying process variables on the resulting characteristics of DDGS. The drying process is also a granulation process, where wet solids are broken up (pulverized) and/or agglomerated into granulated, flowable materials (Probst and Ileleji, 2009). Having a liquid in the blend (i.e., CDS) during drying induces particle agglomeration, and results in spherical ball-shaped solids, which are often referred to as “syrup balls” in the industry. The size of agglomerates depends on the level of CDS in the blend, the physical process of introducing and blending the CDS with the DWG and recycled DDGS, dryer rotation speed, as well as the total number of dryer revolutions. Compared to newer plants, DDGS from older generation plants that use rotary dryers are typically darker in color, have a larger geometric mean particle size (d$_g$ of 3 mm or more), and have a larger particle size distribution. The large agglomerates occur in these older systems because of the way the CDS is introduced into the blend—often all at once, which precludes thorough mixing with

the DWG and recycled DDGS. It should also be noted that the partial recycling of dried DDGS to reduce the energy requirements for drying, prevent plugging of the dryer, as well as speed up drying has the potential to cause product degradation due to denaturing of proteins (especially heat-sensitive amino acids) and other components that are repeatedly exposed to high temperatures.

Another type of rotary dryer configuration that is becoming commonly installed at newer dry grind ethanol plants consists of a pair of rotary drum dryers connected in series. In this configuration, the blend of DWG, CDS, and freshly recycled DDGS enters the first dryer, which dries the product to between 25% and 35% moisture content. The DDGS discharging from the second dryer, on the other hand, is between 10% and 12% moisture content. A portion of the DDGS from each dryer is recycled back through that specific dryer, along with the incoming material stream (DWG and CDS for the first dryer; partially dried DDGS and new CDS for the second dryer). Generally about four times more CDS is added to the second dryer versus the first. This newer configuration produces DDGS that is lighter (golden) in color, has a smaller particle size (generally less than 2 mm), and has a narrower particle size distribution. The decrease in particle size is correlated to a decrease in particle agglomeration during drying, because the addition of the syrup (which is the agglomeration agent) is accomplished in two stages instead of one, which reduces agglomeration formation and enhances bulk pulverization. Additionally, the second dryer
can often be operated at somewhat lower temperatures than the first; this also impacts the resulting DDGS properties (Kingsly et al., 2010).

In recent years, ring dryers have become used at many ethanol plants as well (Figure 5.11 shows a generic schematic for this process). In this type of system, recycled DDGS is mixed with incoming CDS and DWG (as with rotary systems), but then the mixture travels through a disintegrator/disenser (which provides some particle size reduction) where it is introduced into a moving hot air stream. The wet material is then pneumatically conveyed through ductwork in the shape of a “ring,” where the water is partially or totally evaporated from DDGS particles. After traveling around the ring circuit, the air stream and entrained particles travel through a split manifold where the wetter (and thus heavier) particles are separated from the lighter, drier particles. The wetter material falls directly to the disperser for travel through the drying circuit again; the dry DDGS material, on the other hand, is sent through cyclone separators to remove them from the air stream. The clean air is then recycled through the system, while the DDGS is then either conveyed to storage, or recycled through the drying system. Ring drying is a very fast process. Typical residence times in a ring dryer are often only a few seconds in the air stream itself, while those particles that are recycled can spend between 2 and 4 min in the system. Overall, a ring dryer will have higher electrical usage compared to rotary dryers, most of which is used to power the primary fan. But these systems will require lower heat (often between 5% and 10% less). Additionally, a ring dryer will have a smaller “footprint,” requiring less area for the system, but it will require a support tower because the system’s components have a vertical orientation (Figure 5.12). Drying of DDGS has been discussed in more depth in Meredith (2003a, 2003b) and Monceaux and Kuehner (2009).
After drying, the DDGS (or DDG) is transferred to a storage structure (Figure 5.13)—most often a flat storage building (via drag conveyor), discharged into multiple piles, and allowed to cool to ambient temperature (this is known as "curing"). Flat storage buildings (Figure 5.14) are generally of sheet metal construction with steel frames and concrete floors; they are often at least 100 ft x 200 ft (30.5 m x 61 m) in size, and can store between 6000 and 8000 tons (5443 and 7257 t) of DDGS. At larger plants, however, concrete silos have become common (Figure 5.13). These can have diameters up to 55 ft (16.8 m), heights up to 110 ft (33.5 m), and often store up to 4000 tons (3629 t). Because DDGS does not generally flow well (as will be discussed in Chapter 7), screw-type reclaim unloaders must be used in these silos. If a large plant does have silos, the DDGS is still generally cured in a flat storage building first; otherwise flowability problems have been shown to become exacerbated. After storage, conveyors are used to transfer the DDGS to the loadout system, which includes a bulkweigher and rail loadout spouting (generally of flexible/retractable design). Capacities for loadout systems generally range from 200 to 400 tons/h (181 to 363 t/h). Sometimes loadout buildings are combined with grain receiving operations in a common structure (as in Figure 5.2).
Manufacturing of Fuel Ethanol and Distillers Grains

DWG, on the other hand, is placed in outdoor concrete bunkers (Figure 5.15). Depending upon the season and prevailing weather conditions, DWG is extremely susceptible to spoilage (due to the high moisture content and water activity), so ethanol plants try to sell the DWG before it degrades (often less than one week). If this occurs, then the product must be disposed of—generally by landfilling. When the product is sold, it must be shipped. Most often, local livestock producers

FIGURE 5.14 Distillers dried grains with solubles (DDGS) are most often piled into a flat storage building until cooled, at which time the DDGS will be transferred and loaded onto rail cars or semitrucks (photograph courtesy of USDA).

FIGURE 5.15 Distillers wet grains (DWG) being piled into a concrete bunker, awaiting loading onto livestock producers’ trucks (author’s photograph).
provide their own trucks (as opposed to the ethanol plants shipping the DWG), and they arrive at the plant when they need to procure the material for their animals. Due to its semisolid nature, and thus challenging material handling behavior, the DWG must be loaded onto semitrailers with a pay loader. Interestingly, the DWG and the CDS have completely different flow characteristics (semi-solid vs. fluid), even though their solids contents can be very similar.

5.1.2 Effects of Processing Conditions on DDGS

Although other chapters in this book are dedicated to the chemical composition (Chapter 8) and physical properties (Chapter 7) of DDGS, it is appropriate to briefly discuss the effects that processing conditions may have on these attributes. Theoretically, all unit operations will ultimately have an influence on the resulting DDGS. Thus grinding, cooking, fermentation, distillation, centrifugation, evaporation, blending, and drying will all play a role, as will the blend ratio of CDS to DWG prior to drying. Moreover, the quality of the incoming corn will also influence the final coproducts as well. Practically speaking, however, some processing steps and parameters are more influential than others. Unfortunately, there have been very few studies to date that have tried to quantify these effects. Han and Liu (2010) collected samples of various process streams throughout the dry grind process (i.e., ground corn, raw slurry, cooked slurry, liquefied mash, fermented mash, whole stillage, DDG, DWGS, and DDGS), and determined the proximate compositions of each, in order to quantify chemical changes during processing. Additional discussions regarding the effects of processing on composition can be found in Chapter 8.

One of these studies, Liu (2009a), examined the particle size distributions (0.15 to 2.36 mm) of both raw ground corn and resulting DDGS samples from six commercial ethanol plants. This study found that the particle size of the raw corn and the DDGS were indeed highly correlated \((r = 0.81)\), which logically makes sense. Overall, the geometric mean diameter \((d_{gw})\) of the ground corn ranged from 0.43 to 0.52 mm; that of the DDGS ranged from 0.48 to 0.70 mm. Thus, the grinding unit operation does impact the DDGS particles.

Another question that needs to be answered is: what effect does the addition level of CDS have upon the DDGS? To investigate the effects of CDS/DWG ratio on resulting chemical composition of DDGS, Cao et al. (2009) conducted a laboratory study. CDS was combined at five levels with DWG (0%, 23%, 40%, and 100% [i.e., no DWG]), and then the samples were oven dried to produce DDGS. As shown in Figure 5.16, the nutrient composition of the CDS played a progressively important role as the CDS increased in the blend. As the level of CDS grew, both the crude protein and the NDF values declined, specifically because the CDS was low in each of these components. Conversely, the crude fat and ash increased with increasing levels of CDS. Also of note, both \(P\) and the \(S\) (which are elements that are very important to livestock diet formulations) increased as the CDS increased. These results underscore the importance of blending a consistent level of CDS to the DWG at the ethanol plant in order to produce DDGS with consistent nutrient properties and low variation.

Along these lines, Kingsly et al. (2010) examined the effects of varying CDS addition levels on various physical and chemical properties of DDGS, but on a commercial scale. Three levels of CDS addition were used: 0 L/min (0 gal/min), 106 L/min (28 gal/min), and 212 L/min (56 gal/min). In this study, DDGS was manufactured using two rotary dryers in series; the first dryer used an inlet temperature of approximately 487°C (909°F), and an outlet temperature of 106°C (223°F); the second dryer had a varying inlet temperature (273°C (523°F), 377°C (711°F), and 499°C (930°F), in order to properly process the varying level of CDS), but the outlet temperature was nearly constant at 109°C (228°F); for all treatments, the speed of the recycling conveyor was held constant at 60% of the maximum. As shown in Figure 5.17, varying the level of CDS resulted in substantial changes in the DDGS properties—both the physical properties as well as the chemical composition. Moisture, geometric mean particle diameter \((d_{gw})\), bulk density, fat, and ash levels all increased linearly as the level of CDS increased. Protein and Hunter L scale (which is a color parameter that quantifies
The addition level of CDS have been combined at five levels with the samples were oven dried and the CDS played a pronounced effect. As the CDS grew, both the NDF was low in each of these CDS levels. Also of livestock diet formulations) Rosentrater and Wrenn (2009) conducted physical flowability property analyses on DDGS samples that were produced under a series of varying conditions in order to investigate the effects of various manufacturing operations (specifically, ethanol processing [i.e., front-end processing conditions] and DDGS drying conditions [i.e., back-end processing conditions]) on the resulting properties of the DDGS. The experiments that focused on front-end variables were primarily concerned with how liquefaction, saccharification, and solids processing conditions (e.g., factors that influence fermentation performance) impacted the resulting DDGS. The trials that examined drying conditions, on the other hand, were primarily concerned with the flowrates of CDS and DWG, as well as dryer temperature. They measured DDGS angle of repose (AOR), aerated (i.e., loose) bulk density (ABD, kg/m³), Hausner Ratio (HR, -), and uniformity (-). Processing conditions that were varied included hammer mill screen size (0.06 to 0.11 in; 1.52 to 2.79 mm), jet cooker temperature (225°F to 235°F; 107°C to 113°C), slurry enzyme flowrate (0 to 103 gal/h; 0 to 390 L/h), mash tank enzyme flowrate (0 to 207 gal/h; 0 to 784 L/h), CDS flowrate (0 to 18 kg/h; 0 to 40 lb/h), DWG flowrate (0 to 57 kg/h; 0 to 126 lb/h), and dryer temperature (153°F to 243°F; 67°C to 117°C).

During the experiments, several processing conditions were held constant, including a corn feed

rate of 500 lb/h (227 kg/h), a process water temperature of 200°F (93.3°C), a process water density of 0.96 g/cm³ (60.5 lb/ft³), a jet cooker flow rate of 3 gal/min (11.4 L/min), a fermentor volume of 3600 gal (13,627 L), a fermentor temperature of 90°F (32.2°C), and a corn solids density of 1.47 g/cm³ (92.6 lb/ft³). In terms of front-end effects, they found that as hammer mill screen size increased (i.e., ground corn particle size increased), the bulk density decreased (Figure 5.18). Additionally, they found that as the enzyme flowrates increased, both the angle of repose and the bulk density of the DDGS increased. Regarding the back-end variables, they found that as the CDS level increased, the bulk density tended to increase as well, but the uniformity of the particles decreased (i.e., they became more nonuniform, and thus varied in shape).

5.1.3 RESOURCE CONSUMPTION DURING MANUFACTURE

After having discussed the production processes that are used to manufacture both ethanol and coproducts, as well as the influences that processing variables may have on the resulting coproduct properties, it is appropriate to briefly quantify how much energy and water are required for these processes. This topic has been one of interest, not only from the manufacturer’s standpoint (because these requirements affect the bottom line for each plant), but also from a net energy
### Chemical properties of commercial DDGS


8°C, a process water density of 1.02 g/mL, a fermentor volume of 20 m³, a process water density of 1.47 g/mL, a mill screen size increased from 3 to 5 mm (Figure 5.18). Additionally, the density of the resulting coproduct as the CDS level increased, with a decrease in the mass of the coproduct particles (i.e., they became larger).

![Graph](image)

**FIGURE 5.18** Effects of front-end (a) and back-end (b) processing conditions on the resulting physical properties of pilot scale-produced DDGS. AOR is angle of repose; ABD is aerated bulk density; HR is Hausner Ratio. (Adapted from Rosentrater, K. A., and B. A. Wrenn, 2009. *Examining the Effects of Ethanol Processing and Drying Conditions on the Physical Properties of Distillers Dried Grains with Solubles (DDGS).* ASABE Paper No. 095563. St. Joseph, MI: ASABE.)

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Balance sustainability and lifecycle assessment standpoint (as mentioned in Chapter 2). Table 5.1 provides some estimates for the total energy and water that are required (on a per gallon of ethanol basis). The table illustrates that over time, energy and water use has been declining industry-wide. This trend is attributable to increases in efficiencies in the plants, which is partly due to new technologies being developed and deployed.
### TABLE 5.1
Estimates of Resource Consumption during Ethanol Manufacturing

<table>
<thead>
<tr>
<th>Year</th>
<th>Ethanol Yield (gal/bu)</th>
<th>Total Energy Use (BTU/gal)</th>
<th>Natural Gas Use (BTU/gal)</th>
<th>Electricity Use (kWh/gal)</th>
<th>Water Use (gal H₂O/gal)</th>
<th>DDGS Production (dry lb/gal)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>2.53</td>
<td>53,277</td>
<td>37,000</td>
<td>1.2</td>
<td></td>
<td></td>
<td>Shapouri et al. (1995)</td>
</tr>
<tr>
<td>1998</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Keeney and Muller (2006)</td>
</tr>
<tr>
<td>2002</td>
<td>2.64</td>
<td>39,719</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shapouri et al. (2002); Wu (2008)</td>
</tr>
<tr>
<td>2005</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.5–6.0</td>
<td>Keeney and Muller (2006)</td>
</tr>
<tr>
<td>2006</td>
<td>2.80</td>
<td>34,000</td>
<td></td>
<td>0.75</td>
<td></td>
<td></td>
<td>Patzek (2007)</td>
</tr>
<tr>
<td>2008</td>
<td>2.62–2.96 (2.81)</td>
<td>17,706–44,034 (31,070)</td>
<td>16,000–36,883 (27,589)</td>
<td>0–1.57 (0.70)</td>
<td>2.65–4.90 (3.45)</td>
<td>4.7–8.1 (5.9)</td>
<td>Wu (2008)</td>
</tr>
</tbody>
</table>

**Note:** Values in parentheses indicate mean values.

### 5.2 FRONT-END FRACTIONATION

Front-end fractionation techniques offer opportunities to use various corn components in high-value food and industrial applications, as the separations occur before any of the ethanol unit operations. A few examples of experimental fractionated products are provided in Table 5.2, and some commercially developed products are listed in Table 5.3. Due to economic conditions in recent years, however, not all of these are actually available. These new processes have led to a burgeoning of coproducts of various compositions that are now available to livestock producers.

#### 5.2.1 DRY FRACTIONATION OF CORN FOR ETHANOL PRODUCTION

Dry milling has historically been a process used for the production of food-grade corn flours, meals, and grits for various uses in the food and beverage industry. In dry milling of corn (Figure 5.19), the kernel is physically separated, using a dry process, into its primary components in which the germ (which contains the fat), tip cap, and pericarp (which contains fiber) are separated from the endosperm (which contains the starch) (Rausch and Belyea, 2006). This general process has also begun to be applied as a prefractionation method prior to fermentation in dry grind ethanol plants. In the ethanol industry this is known as dry fractionation, and a number of different dry milling technologies to fractionate corn are currently being retrofitted into existing dry grind fuel ethanol plants. The economics and value of dry fractionation lie in the fact that only the fermentable portion of the kernel, the endosperm, is ground and fermented into ethanol, while the other nonfermentable components (i.e., protein, fiber, oil, and tip cap) can be processed into other higher value products. Rausch and Belyea (2006) describe the dry milling process as follows: (1) corn kernel moisture content is first increased from approximately 15% to 22%, which causes differential swelling of the
TABLE 5.2

Some Experimentally Fractionated Ethanol Coproducts

<table>
<thead>
<tr>
<th>Product</th>
<th>Type of Fractionation</th>
<th>Crude Protein</th>
<th>Crude Fat</th>
<th>Crude Fiber</th>
<th>ADF</th>
<th>NDF</th>
<th>Ash</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefermentation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DDGS</td>
<td>No fractionation</td>
<td>28.5</td>
<td>12.7</td>
<td>10.8</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6</td>
<td>Singh et al. (2005)</td>
</tr>
<tr>
<td>DDGS</td>
<td>Quick germ process</td>
<td>35.9</td>
<td>4.8</td>
<td>8.2</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>Singh et al. (2005)</td>
</tr>
<tr>
<td>DDGS</td>
<td>Quick germ, quick fiber process</td>
<td>49.3</td>
<td>3.8</td>
<td>6.8</td>
<td>4.1</td>
<td>4.1</td>
<td>4.1</td>
<td>Singh et al. (2005)</td>
</tr>
<tr>
<td>DDGS</td>
<td>Enzymatic dry grind process</td>
<td>58.5</td>
<td>4.5</td>
<td>2.0</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>Singh et al. (2005)</td>
</tr>
<tr>
<td>DDGS</td>
<td>No fractionation</td>
<td>21.2</td>
<td>13.9</td>
<td>4.0</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>Martinez-Amezcua et al. (2007)</td>
</tr>
<tr>
<td>DDGS</td>
<td>Dry degerm defiber</td>
<td>23.8</td>
<td>8.7</td>
<td>5.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>Martínez-Amezcua et al. (2007)</td>
</tr>
<tr>
<td>DDGS</td>
<td>Quick germ, quick fiber process</td>
<td>28.0</td>
<td>5.4</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>Martínez-Amezcua et al. (2007)</td>
</tr>
<tr>
<td>Postfermentation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DDGS</td>
<td>Elusieve</td>
<td>33.6</td>
<td>12.5</td>
<td>32.5</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>Srinivasan et al. (2005)</td>
</tr>
<tr>
<td>Pan DDGS</td>
<td>Elusieve</td>
<td>42.2</td>
<td>12.9</td>
<td>19.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>Srinivasan et al. (2005)</td>
</tr>
<tr>
<td>Enhanced DDGS</td>
<td>Elusieve</td>
<td>35.6</td>
<td>14.2</td>
<td>32.6</td>
<td>4.7</td>
<td>4.7</td>
<td>4.7</td>
<td>Srinivasan et al. (2005)</td>
</tr>
<tr>
<td>“Fiber”</td>
<td>Elusieve</td>
<td>19.3</td>
<td>7.0</td>
<td>53.3</td>
<td>4.7</td>
<td>4.7</td>
<td>4.7</td>
<td>Srinivasan et al. (2005)</td>
</tr>
<tr>
<td>DDGS</td>
<td>Elusieve</td>
<td>33.0</td>
<td>8.0</td>
<td>37.8</td>
<td>4.7</td>
<td>4.7</td>
<td>4.7</td>
<td>Rosentrater and Srinivasan (2008)</td>
</tr>
<tr>
<td>Pan DDGS</td>
<td>Elusieve</td>
<td>37.3</td>
<td>7.0</td>
<td>29.2</td>
<td>4.7</td>
<td>4.7</td>
<td>4.7</td>
<td>Rosentrater and Srinivasan (2009)</td>
</tr>
<tr>
<td>Enhanced DDGS</td>
<td>Elusieve</td>
<td>31.9</td>
<td>8.7</td>
<td>34.6</td>
<td>4.7</td>
<td>4.7</td>
<td>4.7</td>
<td>Rosentrater and Srinivasan (2009)</td>
</tr>
<tr>
<td>“Fiber”</td>
<td>Elusieve</td>
<td>25.2</td>
<td>6.6</td>
<td>42.3</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
<td>Rosentrater and Srinivasan (2009)</td>
</tr>
<tr>
<td>Deoiled DDGS</td>
<td>Solvent extraction</td>
<td>34.0</td>
<td>2.7</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>Saunders and Rosentrater (2009)</td>
</tr>
<tr>
<td>Deoiled DDGS</td>
<td>Solvent extraction</td>
<td>34.5</td>
<td>3.5</td>
<td>5.2</td>
<td>5.2</td>
<td>5.2</td>
<td>5.2</td>
<td>Kalscheur et al. (2008)</td>
</tr>
<tr>
<td>Deoiled DDGS</td>
<td>Solvent extraction</td>
<td>33.3</td>
<td>4.1</td>
<td>5.1</td>
<td>5.1</td>
<td>5.1</td>
<td>5.1</td>
<td>Ganesan et al. (2009)</td>
</tr>
</tbody>
</table>

Note: All Nutrients Reported as % Dry Basis. ADF is acid detergent fiber; NDF is neutral detergent fiber.

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Corn components in high-value coproducts in Table 5.2, and some for the production of ethanol unit operations. In recent years, dry grind ethanol plants have led to a burgeoning of producers.

corn components in high-value of the ethanol unit operations. In Table 5.2, and some corn components in which the fiber) are separated from the other kernel components. This general process has also been used in dry grind ethanol plants. Dry milling of corn involves separation of different dry milling operations: (1) corn kernel moisture differential swelling of the

germ relative to the other kernel components, and increases the resiliency of the germ; (2) the corn is then sent through a degerminator to separate the germ: this is an abrasion step that breaks the kernel into pericarp (i.e., bran), germ, and endosperm fragments; (3) additional steps remove pericarp and germ from the endosperm; and (4) an aspirator and a gravity table are used to further classify and purify the broken pieces of kernel into their respective components.

In comparison to the wet milling process, fractionation of the kernel components is not as complete in the dry milling process. The resulting distillers grains from plants that utilize dry milling fractionation generally has a higher concentration of protein than distillers grains produced using traditional dry grinding, but a lower fiber and oil content, because these components are separated out prior to fermentation. Additionally, dry milling fractionation processes save energy and increase fermentation
### TABLE 5.3
Some Commercially Developed Fractionated Ethanol Coproducts

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Product</th>
<th>Type of Fractionation</th>
<th>Crude Protein</th>
<th>Crude Fat</th>
<th>Crude Fiber</th>
<th>ADF</th>
<th>NDF</th>
<th>Ash</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWS Technologies</td>
<td>Enhanced DDGS</td>
<td>Pre/fermentation</td>
<td>35.0-37.0</td>
<td>6.5</td>
<td></td>
<td>21.0</td>
<td>3.8</td>
<td></td>
<td>FWS (2009)</td>
</tr>
<tr>
<td></td>
<td>Dakota Gold BPX</td>
<td>No fractionation</td>
<td>28.2</td>
<td>10.8</td>
<td>7.1</td>
<td>10.0</td>
<td>26.1</td>
<td>4.8</td>
<td>Dakota Gold (2009a)</td>
</tr>
<tr>
<td></td>
<td>DDGS</td>
<td>Pre/fermentation</td>
<td>14.0</td>
<td>8.9</td>
<td>7.0</td>
<td>8.0</td>
<td>38.1</td>
<td>5.5</td>
<td>Dakota Gold (2009b)</td>
</tr>
<tr>
<td></td>
<td>Dakota Bran</td>
<td>Pre/fermentation</td>
<td>15.8</td>
<td>17.1</td>
<td>6.2</td>
<td>8.2</td>
<td>23.4</td>
<td>5.9</td>
<td>Dakota Gold (2009c)</td>
</tr>
<tr>
<td></td>
<td>Dakota Germ—Corn Germ Dehydrated</td>
<td>Pre/fermentation</td>
<td>41.0</td>
<td>4.0</td>
<td>8.1</td>
<td>13.0</td>
<td>2A</td>
<td>2.1</td>
<td>Dakota Gold (2009d)</td>
</tr>
<tr>
<td></td>
<td>Dakota Gold HP DDG</td>
<td>Pre/fermentation</td>
<td>35.0-50.0</td>
<td>2.5-4.0</td>
<td>7.0-11.0</td>
<td>15.0-25.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renessen Solaris</td>
<td>Enhanced DDG(S)</td>
<td>Pre/postfermentation</td>
<td>30.0</td>
<td>2.5</td>
<td>8.2</td>
<td>9.23</td>
<td>15.3</td>
<td>2.5</td>
<td>Lohrmann (2006)</td>
</tr>
<tr>
<td></td>
<td>Energia</td>
<td>Pre/postfermentation</td>
<td>45.0</td>
<td>3.3</td>
<td>3.8</td>
<td>17.1</td>
<td>4.0</td>
<td>0.6</td>
<td>Lohrmann (2006)</td>
</tr>
<tr>
<td></td>
<td>Glutenol</td>
<td>Postfermentation</td>
<td>6.8</td>
<td>1.5</td>
<td>17.1</td>
<td>6.0</td>
<td>1.9</td>
<td>1.0</td>
<td>Lohrmann (2006)</td>
</tr>
<tr>
<td></td>
<td>Neutra-Fiber</td>
<td>Pre/fermentation</td>
<td>17.5</td>
<td>45.0</td>
<td>6.0</td>
<td>2.0</td>
<td>16.6</td>
<td></td>
<td>Lohrmann (2006)</td>
</tr>
<tr>
<td></td>
<td>NeutraGerm</td>
<td>Pre/postfermentation</td>
<td>9.5</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** All Nutrients Reported as % Dry Basis. ADF is acid detergent fiber; NDF is neutral detergent fiber.
capacity since a highly concentrated stream of starch (which is converted into ethanol) is processed through the fermentors. The economics and value of germ and fiber separation prior to fermentation have been researched and described in Singh and Eckhoff (1997) and Singh et al. (2002).

The dry fractionation process has a number of benefits, but it also has several disadvantages that need to be considered. Dry separation equipment does not cleanly separate the components without losing some starch. If starch is lost with these coproducts, it cannot be converted into ethanol, thus yields will be reduced. Additionally, the soluble components in the germ contain important nutrients for yeast metabolism. When the germ is removed using dry separations, these nutrients are removed as well. Without these being available to the yeast, metabolism can be significantly reduced and fermentation rates and yields decreased. Lastly, while the overall coproduct drying costs are reduced relative to the conventional process, electricity use is significantly increased for the various fractionation equipment.

Several variations of dry fractionation have been developed and commercially implemented (Table 5.3), including BFrac (www.poet.com), FWS (www.fwstl.com), Cereal Process Technologies (www.cerealprocess.com), and dry degerm defiber (Murthy et al., 2006) technologies. Singh and Johnston (2009) have provided an extensive discussion regarding dry fractionation techniques for dry grind plants, and the reader is referred to this source for more information.

5.2.2 WET FRACTIONATION OF CORN FOR ETHANOL PRODUCTION

In the corn wet milling process (Figure 5.20), the corn kernel is fractionated into individual components of starch, protein, fiber, germ, and soluble solids using an aqueous medium (Bianchard, 1992; Johnson and May, 2003). The process involves multiple stages, including chemical pretreatment using sulfites, followed by size and density separations to produce the isolated components. Wet milling is currently used to produce a significant portion (over 1 billion gallons [~ 3.8 billion L]
per year) of fuel ethanol; however, as previously mentioned, capital and operational costs are high relative to the dry grind process (Ramirez et al., 2009), so the majority of new facilities have been dry grind in recent years.

A number of prefractionation processes using wet milling unit operations have been developed for use in dry grind plants. As with the dry fractionation techniques, these processes separate out the higher value germ and can remove fiber as well. One process developed also incorporates an enzyme treatment that aids in the subsequent separation and fermentation processes (Ramirez et al., 2009). Unlike dry fractionation, however, wet fractionation also can remove the endosperm fiber and extract the soluble nutrients from the germ. Wet fractionation can also have higher starch recoveries relative to dry fractionation; however, all components must be hydrated, so the overall coproduct drying costs will be higher than traditional dry grind plants.

Several variations of wet fractionation have been developed, and include the quick germ process (Singh and Eckhoff, 1997), the quick germ quick fiber process (Wahjudi et al., 2000), and the enzymatic milling process (Wang et al., 2005). Singh and Johnston (2009) have provided an extensive discussion regarding wet fractionation techniques for dry grind plants, and for the sake of brevity, the reader is referred to this source for more information.

5.3 BACK-END FRACTIONATION

In addition to fractionating nutrients from the raw corn kernels prior to fermentation, another possibility that has been explored in recent years is the fractionation of nutrients from the coproducts themselves (i.e., postfermentation). To date, most of the interest in this type of fractionation has primarily revolved around the DDGS, the thin stillage, or the CDS. A few examples of experimental fractionated products are provided in Table 5.2, and some commercially developed products are listed in Table 5.3. As these tables show, the various fractionation processes can lead to coproducts

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with substantially unique nutrient compositions. A brief discussion about various back-end fractionation options follows; but more extensive discussions about each will be provided in subsequent chapters.

### 5.3.1 Fractionation of Components from DDGS

The idea of removing chemical components from ethanol coproducts has actually been around for quite some time. An early example of concentrating nutrient streams was described in Wu and Stringfellow (1986), who found that a simple screening method (using sieves) could result in finer particle fractions with substantially higher protein content, as well as lower fiber, compared to the initial materials, for both corn DDG and DDGS. Composition of the screened DDG fractions depended on the mesh size (ranging from 20 through 80 mesh; 0.84 to 0.18 mm), and resulted in 14.5% to 49.3% protein, 8.4% to 9.3% fat, and 1.3% to 2.4% ash content (on a dry basis); screened DDGS, on the other hand, yielded protein contents ranging from 16.9% to 36.8%, fat contents of 7.4% to 12.0%, and ash contents of 2.0% to 6.5%.

In another early study, Wu and Stringfellow (1982) fractionated corn DDG (using moisture contents between 6% and 31%) and corn DDGS (using moisture contents between 5% and 31%). The materials were first milled and then screened on various sieves (ranging from 20 through 80 mesh; 0.84 to 0.18 mm). The original DDG had 30% protein content, while the resulting fractions ranged in protein from 11% to 46%. Optimal DDG processing conditions were found to be 21% moisture with two passes through the mill at 14,000 rpm. The original DDG, on the other hand, had a protein content of 25%, while the resultant fractions ranged in protein from 13% to 50%; optimal conditions were determined to be similar to those for the DDGS—21% initial moisture content but only one pass through the mill at 14,000 rpm. They also found that, for both the DDGS and the DDG, the fractions that had the highest protein also had the highest fat levels. And fiber appeared to be resistant to grinding, as the fractions with the largest particle size tended to have the highest fiber content.

Air aspiration can also be used to separate fiber from DDGS. Singh et al. (2002) examined samples from both corn-based dry grind ethanol plants in the Midwest, and beverage alcohol plants that used combined feedstocks consisting of corn, rye, and malted barley. An aspiration technique, which entailed placing DDGS on a 20 mesh (840 μm) screen and then aspirating with an air jet at a pressure of 2.8 atm, (284 kPa) was able to separate the pericarp from the germ fraction, though not extremely effectively. Overall, the aspirated DDGS samples contained (on a dry basis) 25.7% to 28.9% protein, 7.7% to 12.3% fat, 39.3% to 51.8% NDF, and 13.1% to 17.9% ADF.

Srinivasan et al. (2005) further expanded these concepts and developed a process (termed the "Elusieve" process) using a combination of elutriation (air classification/aspiration) and sieving to separate fiber particles from DDGS. First, DDGS was sieved into four size fractions, and then the three larger size fractions were subjected to air classification. The smallest size fraction (which was not subjected to air classification), the "pan" DDGS, represented nearly 40% of the original DDGS and had reduced fiber and increased protein content (by approximately 6% to 14%, and 7% to 8% points, respectively) compared to the original DDGS. The three larger size fractions, on the other hand, which were subjected to air classification, yielded heavier and lighter fractions. Air velocity played a key role in this classification. Overall, the resulting lighter fractions had higher fiber and lower protein and fat contents than the heavier fractions, depending on air velocity. The heavier fractions from air classification of the three larger size fractions were then combined together to produce an "enhanced" DDGS product that had nearly same protein content, but lower NDF content, than the original DDGS. The lighter fractions from air classification of the three larger size fractions were combined together to produce a "Fiber" product, which had higher NDF and lower protein and fat contents than the original DDGS. Liu (2009b) also examined the effects of combining sieving and air separation. This study found that, depending on the particle (i.e., sieve) size used, a maximum protein reduction of 56.4% and a maximum protein increase of 60.2% could...
be achieved. Additionally, oil could be reduced by as much as 81.4%, or increased by as much as 262.7%. The topic of mechanical fractionation will be covered in more depth in Chapter 25.

Another possibility for fractionation includes the removal of oil from the DDGS, which can readily be accomplished by solvent extraction. Singh and Cheryan (1998) were the first to report successful solvent extraction of corn oil from DDGS. Their optimal process entailed using a ratio of ethanol-to-DDGS of 6:1, and this resulted in extraction of nearly 50% of the oil. In general, if the oil is removed after ethanol processing, its quality is not high enough to be appropriate for food use; but it has been shown to be acceptable for conversion into biodiesel (more about this will be discussed in Chapter 23). The process of removing the oil will not only affect the DDGS composition, but it can also impact the physical nature of the particles. For example, Saunders and Rosentrater (2009) examined chemical and physical properties of commercially processed solvent extracted DDGS. Crude fat levels (2.7% db) were much lower, while crude protein (34.0% db) and crude fiber (8.4% db) contents were somewhat higher than traditional DDGS. The resulting DDGS exhibited water activity (0.24), thermal conductivity (0.07 W/m°C), thermal diffusivity (0.17 mm²/s), bulk density (482 kg/m³; 30.1 lb/ft³), and angle of repose (21.7°) values similar to unmodified DDGS. Color values were substantially lighter (Hunter L = 54.1 compared to ~40 to 50 for unmodified DDGS), however, because of fat-soluble pigment losses during processing. Similarly, Ganesan et al. (2009) examined physical and flowability properties of commercially produced solvent-extracted (2.1% db fat) and unmodified (9.3% db fat) DDGS to determine if fat level affected flowability behavior. The extracted DDGS had an angle of repose 4.3% lower and Carr compressibility 70% lower than unmodified DDGS. Jenike shear testing indicated that reduced fat DDGS had unconfined yield strength and Jenike compressibility values that were 15.7% and 40.0% lower, respectively, than unmodified DDGS, but had major consolidating stress and flowability index values that were 6.7% and 13.2% higher. Overall, a reduction in fat content slightly improved some flow properties, but both types of DDGS were ultimately classified as cohesive in nature.

5.3.2 Fractionation of Components from Liquid Streams

In recent years interest has grown in removing corn oil from liquid coproduct streams prior to the drying operation. This is not a new concept, however. Wu et al. (1981) examined fractionation of whole stillage using screening (20 mesh; 0.84 mm) and centrifugation (10,400 xg for 10 min). Although the focus of their work was to concentrate protein, they were also able to produce streams that had fat contents concentrated up to 36% more than the level found in DDGS.

As the fuel ethanol industry has grown, commercial processes have been developed to remove corn oil from thin stillage, semiconcentrated thin stillage, and even CDS, in order to increase revenue for ethanol plants. This type of fractionation has been pursued because, although the resulting corn oil fractions cannot be used as food-grade oil, they can readily be converted into biodiesel. More on this will be covered in a Chapter 23.

Some of the processes that are currently being deployed include those of Mean Green BioFuels (www.meangreenbiofuels.com; Winsness, 2006), GS CleanTech (www.greenshift.com; Kirkbride McElroy, 2007; Cantrell and Winsness, 2009; Winsness and Cantrell, 2009), and ICM (www.icminc.com; ICM, 2009). In general, all of the processes that are currently available are based upon physical separation techniques, using various configurations of decanters and centrifuges, and have been reported to remove between 30% and 70% of the oil in the coproduct stream.

5.4 Coproduct Definitions

As discussed, there are a variety of fuel ethanol coproducts than can potentially be produced at a given plant. Each plant is unique, and employs various permutations of processing technologies. In terms of end use (i.e., feeding to livestock), it is important for livestock producers to understand specifically what they are purchasing. To facilitate the sale and fair trade of coproducts in the
Manufacturing of Fuel Ethanol and Distillers Grains

TABLE 5.4

<table>
<thead>
<tr>
<th>Common Acronym</th>
<th>Official Name</th>
<th>Official Definition for Trade</th>
</tr>
</thead>
<tbody>
<tr>
<td>DDGS</td>
<td>Corn Distillers Dried Grains with Solubles</td>
<td>&quot;Is the product obtained after the removal of ethyl alcohol by distillation from the yeast fermentation of a grain or a grain mixture by condensing and drying at least ¾ of the solids of the resultant whole stillage by methods employed in the grain distilling industry. The predominating grain shall be declared as the first word in the name.”</td>
</tr>
<tr>
<td>DDG</td>
<td>Corn Distillers Dried Grains</td>
<td>&quot;Is obtained after the removal of ethyl alcohol by distillation from the yeast fermentation of a grain or a grain mixture by separating the resulting coarse grain fraction of the whole stillage and drying it by methods employed in the grain distilling industry. The predominating grain shall be declared as the first word in the name.”</td>
</tr>
<tr>
<td>DWG (WDG)</td>
<td>Distillers Wet Grains</td>
<td>&quot;Is the product obtained after the removal of ethyl alcohol by distillation from the yeast fermentation of a grain mixture. The guaranteed analysis shall include the maximum moisture.”</td>
</tr>
<tr>
<td>CDS (syrop)</td>
<td>Corn Condensed Distillers Solubles</td>
<td>&quot;Is obtained after the removal of ethyl alcohol by distillation from the yeast fermentation of a grain or a grain mixture by condensing the thin stillage fraction to a semi-solid. The predominating grain must be declared as the first word in the name.”</td>
</tr>
<tr>
<td>DDS</td>
<td>Corn Distillers Dried Solubles</td>
<td>&quot;Is obtained after the removal of ethyl alcohol by distillation from the yeast fermentation of a grain mixture by condensing the thin stillage fraction and drying it by methods employed in the grain distilling industry. The predominating grain must be declared as the first word in the name.”</td>
</tr>
</tbody>
</table>

5.5 CONCLUSIONS

This chapter was intended to provide a broad overview of the production methods that are commonly used to manufacture both fuel ethanol and the concomitant coproduct streams from corn. Other grains can also be used; these will be discussed in the following chapter. The industry is dynamically evolving, so the fractionation techniques that have been discussed will most probably grow in use during the coming years. And newer technologies that will improve energy efficiency and decrease water use throughout the plant, as well as improve the ethanol yield, will undoubtedly continue to be refined. The ultimate impact of these modifications will be upon coproduct properties, and thus, utilization opportunities.

REFERENCES


Manufacturing of Fuel Ethanol and Distillers Grains


