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Coproducts from Bioprocessing of Corn

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Abstract. *Increase in demand for ethanol as a fuel additive has resulted in dramatic growth in ethanol production. Ethanol is produced from corn by wet milling or dry grind processing. Wet mill plants are capital intensive due to equipment requirements; they produce large volumes of ethanol and are corporate owned. In dry grind processing, the kernel is not fractionated and only one coproduct, distillers dried grains with solubles (DDGS), is generated. Dry grind plants require less equipment and capital than wet mills. They generate smaller volumes of ethanol, are producer owned and add direct benefits to rural economies. Most of the increase in ethanol production during the past decade is attributed to growth in the dry grind industry.*

The marketing of coproducts provides income to offset processing costs. For dry grind plants, this is especially important, because only one coproduct is available. The increasing volume of DDGS accompanying ethanol production could reduce market value; high phosphorus content could limit use of DDGS, because of animal waste disposal issues. Water removal is a costly processing step and affects the economics of ethanol processing. Technologies to remove germ and fiber from DDGS could produce a new coproduct suitable for feeding to nonruminants; this would expand the markets for DDGS. Reducing phosphorus in DDGS would sustain markets for conventional DDGS.

Development of more efficient methods of water removal would increase the efficiency of ethanol processing and reduce costs. New technologies could contribute to greater economic stability of dry grind plants.

Keywords. Coproducts, corn processing, bioprocess design, nutrient recovery, process variability, animal diets, ethanol.

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Introduction

Due to governmental efforts to reduce air pollution, the demand for fuel ethanol is increasing. This is driven largely by the Clean Air Act amendment of 1990, which requires the use of oxygenated fuel and reformulated gasoline to reduce carbon monoxide and other pollutants. The amount of corn used for ethanol production has increased 17 fold during the past 20 years to more than 600 million bushels per year (Figure 1); in 2004, ethanol production was 3 billion gallons per year (RFA 2005). Much of the fuel ethanol production capacity in the US is concentrated in Midwestern states, which have large inventories of corn. Corn is converted into ethanol primarily by two processes, wet milling and dry grinding. In wet milling, the corn kernel is fractionated into primary components (germ, fiber and starch); this results in several process streams and coproducts. Wet mills are equipment and capital intensive; they generate large volumes of ethanol and are corporate owned. In dry grind processing, the corn kernel is not fractionated and only one coproduct is produced, distillers dried grains with solubles (DDGS). Dry grind plants require less equipment and are less capital intensive. They produce smaller volumes of ethanol, are producer owned and contribute significantly to rural economies. Traditionally, most ethanol has been produced by wet milling; however, in the past ten years, dry grind capacity has increased rapidly and now accounts for 70% of ethanol production (RFA 2005).

Recent growth trends in the dry grind ethanol industry are expected to continue and will increase the volume of DDGS to be marketed. DDGS is desirable to animal producers because of high protein content; however, it also has high fiber content, which limits its use primarily to ruminant diets. It is not clear if the ruminant market for DDGS is becoming saturated; that depends on the cost and supply of competitive animal foods (ie, corn and soybean meal). However, there has been a general downward trend in the market price of DDGS during the past two decades (Figure 2). As the supply of DDGS continues to grow, this trend may continue, unless there is an increase in market opportunities.

Many technological improvements have been made in the fermentation and distillation steps of ethanol processing. These changes have increased the efficiency of energy use for ethanol production. Shapouri et al (1995, 2001, 2002) suggest a 67% net energy gain from corn production to the finished product. However, little attention has been given to addressing issues related to quality and marketing of coproducts. For both wet milling and dry grind processing, ethanol will be considered a primary product; other materials will be considered to be coproducts. Marketing of coproducts is important as a source of income to offset costs of producing ethanol. In wet milling, there are several coproducts: corn gluten meal (CGM), corn gluten feed (CGF), crude corn oil and germ meal. In dry grind processing, there is only one coproduct, DDGS, available for marketing. Marketing of coproducts is important for dry grind ethanol plants; their economic sustainability could be strengthened if existing markets could be expanded or new markets could be developed.

There are several impediments to be overcome if new markets are to be developed or existing markets expanded. These include high concentrations of fiber and phosphorus, variability in composition and high cost of water removal. High fiber content limits use of ethanol coproducts mainly to ruminant diets. Reducing fiber concentrations would create a new coproduct(s) that could be used in nonruminant diets; this change could expand market opportunities. High phosphorus concentrations of coproducts will pose important waste disposal challenges for many ruminant producers. Reducing the phosphorus content could reduce these concerns and prevent potential adverse impacts on ruminant markets. Variability in composition of coproducts reduces quality because it results in inaccurate diet formulation. Reducing variability will increase the quality and market value of coproducts. Water removal is a costly and difficult process that can affect coproduct quality; identifying less costly and more effective approaches for removing water will increase processing efficiency and decrease processing costs.

Technologies to address these issues could contribute to greater economic stability of ethanol processing plants by increasing markets, increasing quality and reducing processing costs. Research efforts are needed to develop new technologies or to modify existing technologies to produce a greater variety of coproducts, improve coproduct quality/value and expand markets. The objectives were to (1) review technologies used to convert corn into ethanol, (2) compare characteristics and marketing limitations of coproducts, (3) examine market issues and (4) discuss strategies for modifying and improving processing methods.

Processes for Converting Corn into Ethanol

Corn is converted into ethanol by three commercial processes: wet milling, dry grinding and dry milling. Each process has unique equipment and technologies that impact the characteristics of the resulting processing streams and coproducts. The processes also differ in respect to management structure, volume of ethanol produced and relationship to corn producers. Because each process has different technologies to produce primary products, it is important to know how each process operates and how they differ. Wet milling plants process relatively large amounts of corn, are corporate owned and generate a wide variety of products and coproducts. Typical dry grind plants are smaller, producer owned and have only one coproduct to market. Dry milling plants produce products primarily for human consumption and an array of coproducts used in animal diets; they generate a small amount of the total ethanol production in the US.

Corn Wet Milling

The purpose of wet milling is to isolate and recover starch in a highly purified stream; starch is used to produce starch products, eg, glucose, high fructose corn syrup, ethanol and other chemicals. In wet milling, corn is fractionated into four components (ie, starch, germ, fiber and protein). Five basic processing steps are used to achieve separation: steeping, germ recovery, fiber recovery, protein recovery and starch washing (Figure 3).

In the first step, corn is steeped in a solution of weak sulfurous acid (2000 ppm S as SO_2) for 24 to 48 hr in a semicontinuous steeping system that hydrates and softens the kernel and leaches solubles from the germ. Steeping improves the separation of kernel components and affects starch quality, starch quantity and coproduct characteristics. Light steepwater (4 to 8% solids) is the material remaining after the steeping operation; heavy steepwater (35 to 40% solids) is the material following concentration of light steepwater by evaporation. Steepwater solids contain 45 to 50% total protein (db, as N $\times$ 6.25; Table 1); much of the protein (N) in the steepwater can be in the form of amino acids (Christiansen et al 1965). Steepwater solids contain water soluble proteins originating from the germ and proteins from other corn components which were solubilized by the steeping process. Light steepwater is concentrated to 40% solids (heavy steepwater) using multiple effect evaporators. If plant production is limited by evaporator capacity, partial concentration of steepwater can be attained with membrane filtration (Rausch 2002). Due to high energy costs associated with evaporation and high osmolarity, heavy steepwater is not concentrated to more than 45% solids.

After steeping, germ and fiber fractions are removed by differences in density and particle size, respectively. Germ has lower density than the rest of the kernel components, because steeping increases the fat concentration (Johnson and May 2002). Germ is removed by a system of hydrocyclones, pressed and dried. The fiber fraction, which contains pericarp and cell wall fiber components, is removed with screens. Fiber is combined with heavy steepwater and the blended material is dried to form CGF. CGF accounts for 22 to 24% of initial corn solids entering the wet mill.

The remaining solids are separated into a starch fraction and a protein fraction. The millstream thickener (a centrifuge) adjusts the specific gravity of the starch-protein slurry, which is transferred to the primary separator. The protein fraction (called gluten or gluten protein) is removed using centrifuges. A centrifuge (primary separator) removes most of the gluten protein from the starch, resulting in a slurry with 3% protein. The starch slurry is purified further to remove residual protein with a system of hydrocyclones that increase the starch concentration to more than 99.5% (db, Figure 3).

Gluten protein is concentrated using the gluten thickener centrifuge and further dewatered by vacuum belt filtration and then drying with rotary steam tube or flash dryers. The final dried product, CGM, represents approximately 5% of initial corn solids. CGM has high protein (65 to 67% db) and low fiber content; it is used primarily in nonruminant and companion animal diets.

To produce ethanol, starch recovered by the hydrocyclone system is cooked, liquefied, saccharified and fermented to produce beer. The beer is passed through a distillation system to separate ethanol from water and other soluble solids, referred to as distillers solubles (DS). The wet milling industry uses sequential saccharification and fermentation, in contrast to the dry grind corn processing industry, which has adopted simultaneous saccharification and fermentation (SSF). DS from wet milling fermentation is characterized by high protein and high ash content (Table 1). Residual solids after fermentation are mixed with CGF and used as animal food ingredients. Carbon dioxide from the fermentation process also may be marketed for the beverage industry.

Dry Grind Corn Processing

The dry grind corn process is designed to subject the entire corn kernel to fermentation. The production of fuel ethanol emphasizes maximum yield of ethanol and conservation of process energy. The fuel ethanol process evolved from the process to produce beverage ethanol. However, the beverage ethanol industry is less sensitive to ethanol yield and energy efficiency. Fuel ethanol prices are subject to more commodity pressure compared to higher valued beverage ethanol. Because of processing differences, composition of DDGS from the fuel ethanol industry may differ from that of the beverage ethanol industry.

Dry grind corn processing has lower capital costs than corn wet milling but, unlike wet milling, has only one major coproduct to market besides ethanol (Figure 4). A dry grind facility processing 1,000 tonne/day and producing 150 million L/yr of ethanol will cost $50 million to construct in the US. Basic steps in the dry grind corn process are grinding, cooking, liquefaction, simultaneous saccharification and fermentation, distillation of ethanol and removal of water from stillage to form DDGS (Figure 4). In the dry grind process, the whole kernel is ground with mills to facilitate water penetration during the subsequent cooking process. Two types of mills are used: (1) hammermills, in which rotating hammers and knives reduce corn particle size and (2) roller mills, in which a pair of rolls rotating at different speeds exert a compressive force to affect particle size reduction.

The ground corn is mixed with water, resulting in a slurry which is cooked and mixed with amylase. After the slurry has been liquefied, glucoamylase and yeast are added to the mash and allowed to ferment. At the completion of fermentation, the resulting material (beer) consists of ethanol, water and solids that were not fermented. Beer is released to atmospheric pressure conditions to separate the carbon dioxide and transferred to a holding tank called a beer well. The beer is fed to a recovery system consisting of two distillation columns and a stripping column. The water-ethanol stream is transferred to a molecular sieve where all remaining water is removed using adsorption technology. Purified ethanol is mixed with a small amount of gasoline to produce fuel grade ethanol (Meredith 2003).

Whole stillage is withdrawn from the bottom of the distillation unit and is centrifuged to produce wet grains and thin stillage (Figure 4). Using an evaporator, thin stillage is concentrated to form condensed distillers solubles (called syrup in the industry). This is added to the wet grains process stream and dried to form DDGS. Dry grind processing results in several potential marketable coproducts: ethanol, wet grains, syrup, DDGS and carbon dioxide. The primary market materials for most dry grind processing plants are ethanol and DDGS, although small amounts of wet grains and syrup are marketed. A few processing plants capture and market the carbon dioxide produced from fermentation.

Dry Milling

Corn dry milling is primarily a physical separation process of corn components in which fat contained in the germ is separated from the endosperm. Unfortunately, the term “dry milling” is sometimes used erroneously to describe the dry grind process. The dry milling process begins by increasing kernel moisture from 15 to 22% (Figure 5). This causes differential swelling of the germ relative to the other kernel components and increases resiliency of the germ. Corn is sent through an abrasion step (degermination) that breaks the kernel into pericarp (bran), germ and endosperm fragments. Additional steps remove pericarp and germ from the endosperm products. An aspiration step uses differences in aerodynamic properties to separate pericarp from endosperm. Using differences in density, a gravity table is used to separate whole germ and germ pieces from the remaining endosperm. Separation of corn constituents is not as ideal as in wet milling; small amounts of pericarp and endosperm remain attached to the germ and, therefore, decrease the concentration of oil in the germ fraction. Overall, the coproducts from dry milling process are not as highly concentrated in protein, fiber and oil as those from wet milling (Table 1). Germ obtained from dry milling has lower oil content (26% db; Table 1) than germ from wet milling (35 to 40% db) and is not processed by large scale corn oil extraction facilities.

Endosperm products (flaking grits, smaller grits, meal, flour) are created using a series of size separation steps; these materials are characterized by low protein, low fat and low fiber (Table 1). The premium product of dry milling is the flaking grits; these consist of large pieces of endosperm and are used primarily in breakfast cereals. Smaller classifications of endosperm particles make up milling products such as brewers grits, meal and flour. These are used in a variety of human foods, such as snack and bakery foods. Germ, pericarp (bran) and standard meal process streams are combined with broken corn and are sold as hominy feed (Table 1).

In summary, corn wet milling and dry grind processing account for nearly all ethanol production. The three different processes (wet milling, dry grind and dry milling) use different equipment and processing conditions, which result in coproducts that have different analytical profiles and uses (Table 2). Such diversity has practical implications on economic pressures; wet milling processors have a much wider variety of marketable materials than dry grind processors. Dry grind processors have fewer marketable materials and are more vulnerable to marketing issues. Broadening market opportunities could help increase the economic outlook for dry grind processing plants

Characteristics and Utilization of Coproducts

Characteristics

The methods (wet milling, dry grind and dry milling) for converting corn into ethanol and other useful products use different equipment and processing conditions; these result in processing streams that are different in composition. These processes yield coproducts that differ in quantity and in economic value (Table 3). Coproducts that result from these streams differ in composition (Table 4). It is important to know the unique nutritional characteristics of each coproduct so that possible strategies can be developed to improve market value.

Corn gluten meal

CGM, a coproduct of wet milling, has low fiber (2.4 g/100 g, Table 4) and high protein content (67.1 g/100 g db). Protein and, specifically, certain essential amino acids, make it a valuable protein source for poultry, swine, fish and companion animal foods. Because of its protein content, the market value of CGM often is greater than $330 per tonne (Figure 2), making it a high value coproduct. CGM has relatively high phosphorus concentrations (0.54 g P/100 g db, Table 4), compared to many typical animal diet ingredients. Most nonruminants (growing swine and poultry) have high phosphorus requirements; therefore, high phosphorus concentrations in CGM are an advantage. However, high phosphorus content could be a concern in some dietary situations because of the potential to increase phosphorus in animal wastes and exacerbate waste disposal difficulties. CGM also has high sulfur content (0.70 g S/100 g db). Data are not conclusive, but it is thought that nonruminants can tolerate sulfur concentrations from 0.5 to 0.7 g S/100 g diet (NRC 1980). When CGM is added to typical nonruminant production diets, sulfur concentration of the resulting diet will be below this range and would not be expected to have adverse affects. However, high sulfur concentrations can occur when there are excessive concentrations of certain sulfur containing amino acids; high concentrations of these amino acids can be toxic to young poultry (NRC 1980). The high sulfur concentration of CGM is not associated with these amino acids and does not appear to pose a practical concern. CGM rarely is fed to ruminants, because of high cost; however, if it were to be fed to ruminants, the high sulfur concentration would be a concern.

CGM has other unique characteristics. It can impart a bitter sensation to diets; animals may hesitate to consume diets containing CGM, unless included in small proportions or masked by more palatable ingredients. The concentration of xanthophylls in CGM has been reported to range from 322 to 482 mg/kg (Wright 1987). Because of these concentrations, CGM often is added to poultry diets to improve pigmentation of poultry products. A view commonly held by animal food industry personnel is the composition of CGM can vary substantially from batch to batch. However, there are few published data to document the extent of variation (Rausch et al 2003).

Corn gluten feed

CGF is another coproduct of wet milling. The protein content of CGF (25.6 g/100 g db, Table 4) is greater than most common animal dietary ingredients such as corn, which makes it a widely used ingredient in ruminant production diets. The protein in CGF contains a large soluble fraction (69 g/100 g db), compared to the soluble fraction in corn and DDGS (34 and 33 g/100 g db, respectively; Krishnamoorthy et al 1982). Therefore CGF should be minimized in diets that contain other dietary ingredients with high soluble protein concentrations, such as silages. CGF is characterized by high fiber content (45 g cell wall/100 g db; Table 4), which limits its use to ruminant diets. While protein content makes CGF an attractive ingredient, high phosphorus content (0.82 g P/100 g db; Table 4) is a concern. Most ruminant production diets contain adequate phosphorus concentrations; adding typical amounts (10%) of CGF will increase the phosphorus content of the resulting diet. When ruminants consume diets containing elevated concentrations of phosphorus, excretion is increased (Morse et al 1992). This can create disposal challenges, because environmental regulations for land application of animal wastes are based partly on phosphorus concentration and are becoming more restrictive. Animal producers who have access to cropland with soils having high phosphorus concentrations and/or who have limited cropland for waste disposal must minimize use of high phosphorus dietary ingredients, such as CGF (Dou et al 2001, Rotz et al 2002, Spears et al 2003, Tamminga 1992, Van Horn et al 1996).

CGF has several unique characteristics that render it a valuable dietary ingredient. It has high fiber and low starch concentrations; the fiber is highly digestible by ruminants. Because of these characteristics, CGF can be substituted for grains, such as corn, to reduce the starch load in the rumen. CGF has small particle size; it has little effective fiber and does not invoke much, if any, rumination (chewing) behavior (Firkins 2003). Some long fiber must be included in diets containing CGF for ruminants to sustain normal rumination activities. CGF typically is pelleted, which, along with fine particle size, appears to account for relatively high rates of passage and high digestibility losses (Fellner and Belyea 1991). However, because of small particle size, CGF does not contribute substantially to rumen fill and does not limit intake; cows can consume relatively large amounts of CGF without limiting intake and production (Fellner and Belyea 1991). CGF has a bitter taste that can affect palatability; when CGF is added to diets, cows often will reduce intake until adapted. This adverse response can be minimized if small amounts are added initially.

Some batches of CGF can have a dark appearance, almost the color of dark chocolate. Animal food materials containing protein and starch and subjected to heating can have dark appearance and elevated concentrations of bound (unavailable) protein. Increased levels of bound protein (above basal levels) reduce the useful protein content of a food material. We have measured the bound protein concentration (as pepsin insoluble N) in a limited number of CGF samples that ranged from moderately dark to very dark in appearance. In those samples, we were unable to demonstrate any change in bound protein. Thus, it is not clear if the quality of protein in dark colored CGF necessarily is compromised.

Corn germ meal

Corn germ meal is produced from whole germ following hexane extraction and is characterized by relatively high fiber (13.1% crude fiber) and moderate concentrations of protein (11.5%) and fat (7.7%). Corn germ meal is considered to be a highly desirable ingredient for nonruminant diets because of essential amino acid concentrations (Table 4). It also is used in companion animal diet formulations. There are limited contemporary published data on characteristics of corn germ meal and on performance of animals consuming diets containing this coproduct (Wright 1987, Loy and Wright 2003).

Distillers dried grains with solubles

DDGS is the only coproduct from the dry grind processing of corn into ethanol. Because the corn kernel is not fractionated, DDGS from dry grind processing contains a mixture of ether extract (crude fat), fiber, protein and elements in relatively high concentrations (Table 4). High fiber content limits the use of DDGS to ruminant diets; however, because of high protein and fat (energy) contents, DDGS is used widely as a dietary ingredient for ruminants with large demand for nutrients (eg, lactating or growing animals). DDGS protein is characterized by a small soluble fraction (33 g/100 g db) and a large fraction (67 g/100 g db) slowly degraded in the rumen (Krishnamoorthy et al 1982). Consequently, DDGS often is used to increase the ruminally undegradable protein fraction of ruminant production diets; this gives DDGS a distinct advantage over other coproducts, such as CGF. Similar to CGF, high phosphorus content of DDGS (0.71 g P/100 g db; Table 4) is a concern, because it increases the phosphorus content of diets and animal wastes, which can lead to disposal challenges. The sulfur content of DDGS based on published data is not high (0.33 g S/100 g db; Table 4). However, the sulfur content of DDGS from dry grind plants appears to be higher than published data. Shurson et al (2001) reported the mean concentration of sulfur in 118 samples of DDGS from dry grind plants was 0.51 g S/100 g db, with a range of 0.33 to 0.68 g S/100 g db. We (Clevenger et al 2004) have limited data that corroborate the data of Shurson et al (2001). High dietary sulfur concentration is a concern; it can lead to excessive sulfide concentrations in the rumen, because of the highly reduced state of ruminal contents. High levels of sulfide can cause a shift in the ruminal microbial population to include bacteria that produce high levels of thiaminases. This reduces the thiamin available to be absorbed from the rumen and results in an effective thiamin deficiency. Thiamin deficiency causes brain lesions (polyoencephalamalacia). The bacteria also produce an analog that inhibits certain enzymes involved in energy metabolism (Kung et al 1998).

DDGS is palatable to animals; ruminants readily consume diets containing DDGS (Schingoethe et al 1983). The high fat content of DDGS (10.3 g/100 g db) can impose intake limits under certain conditions. DDGS is not pelleted, but the meal form is easy to handle in mechanical systems. While some of the DDGS is sold in wet form, most is dried prior to marketing. Wet DDGS is prone to deterioration, especially in warmer weather; consequently, use of wet DDGS is limited to producers located close to the dry grind plant.

There is considerable discussion regarding the color of DDGS and nutritional quality. The normal (or at least preferred) color of DDGS is golden brown. It is not uncommon to observe a range of colors from golden brown to very dark among batches of DDGS. Recently, we obtained samples of dark DDGS as well as normal colored samples. We analyzed these samples for bound protein content (as pepsin N). We found the bound protein was increased in some samples but not all. Powers et al (1995) fed normal and dark colored DDGS to lactating cows; cows fed the dark DDGS had reduced milk protein synthesis due to increased bound protein (less available protein). It is difficult to quantify color of DDGS; however, Powers et al (1995) estimated that dark colored DDGS had 21% of the total protein in the bound fraction, compared to 13% for the normal DDGS (a 61% increase in bound protein content).

Syrup (condensed distillers solubles)

While DDGS is the main coproduct that dry grind plants market, they occasionally market syrup. Because syrup is difficult to produce as a free flowing powder, it is handled in liquid form and added directly to diets as a liquid dietary ingredient. Because of high water content, its use is limited to local producers. Syrup typically contains 30 to 40% dry matter; solids contain 40 g protein, 15 g ash, 20 g fat and 25 g other material/100 g (Table 4). Concentrations of many elements, such as Na, K and phosphorus are high; presence of elements in high concentrations raises questions about physiological effects on animals consuming diets containing syrup and on waste disposal issues.

Wet grains

Wet grains sometimes are marketed by dry grind processors. There are limited data on nutritional profiles of wet grains. Wet grains were characterized by NRC (1982) as containing 43% nondetergent fiber (NDF), 23% protein, 12.1% crude fiber, 9.8% fat and 2.4% ash. It is not clear what the source of sample(s) was for these data; it is unlikely they represented modern dry grind processing. Limited data from our laboratory is suggestive that wet grains from dry grind processing have lower fiber and higher protein (30%) and higher fat (13%) than wet grains data reported in NRC (1982). Mineral concentrations of wet grains appear to be low (eg, 0.11% Ca, 0.43% P, 0.18% K; NRC 1982).

Hominy feed

Hominy feed, or hominy, is characterized by relatively high fiber (6.7% crude fiber), low protein (11.9%) and moderate fat (4.2%) content (Table 4). It generally is in meal form; it is bulky; therefore, handling and storage can be issues. However, it can be incorporated into blended ruminant diets. Hominy contains pericarp, germ and some starch from the endosperm. Due to the fat content, it has an energy value similar to corn. Hominy is used in ruminant diets and is palatable despite its small particle size. Its rate of digestion is higher than corn. The decision to use hominy depends on market price; low protein content can reduce its competitiveness and result in low usage. Hominy is used most commonly by producers in the Midwest, apparently because of close proximity, lower cost and availability.

Coproduct Utilization and Marketing Issues

In ethanol production, coproducts are marketed to add value to processing. For dry grind plants, income from the marketing of DDGS offsets much of the cost of ethanol production; this is an important economic contribution that must be sustained. Marketing reflects the interests of ethanol processor and end user (animal producer). Because ethanol is a primary product, plant managers often devote most of their time and resources to manage the processes and equipment used to convert corn into ethanol. They often do not have time nor resources to address some issues associated with coproduct quality. This is complicated by lack of basic information needed to address certain problems. For example, DDGS composition can have large fluctuations. Causes of the variation are not well documented; this impairs development of management strategies to control variation as well as other quality issues.

Because it is difficult for processors to control quality issues, such as variation, the market value of DDGS is less than optimal; if the protein content were high and consistent, DDGS would be viewed by end users as a more competitive and more valuable ingredient. However, animal producers usually have available a wide variety of food ingredients from a number of sources that can be considered for diet formulation. These include coproducts from the processing of corn, soybeans, cotton and rice as well as other conventional materials. Producers are able to select the most economical dietary ingredient(s). This places pressure on the marketing of ethanol coproducts.

Factors that affect the decision to purchase coproducts

Animal producers may purchase coproducts for a variety of reasons. However, the primary reason, by a large margin, is economic. Dietary ingredients generally are the single largest expense in animal production. Most animal producers formulate diets with ingredients that minimize costs and support optimal productivity. Selecting the most economical ingredients can be complicated because of differences in composition of ingredients and differences in cost. Computer programs (spreadsheets) can be used to provide relative comparisons of economic value of coproducts (and other dietary ingredients) compared to conventional ingredients (Howard and Shaver 1997). These programs take into account several nutrient concentrations, although energy and protein are primary determinants. The programs estimate what often is referred to as a break even price or maximum purchase price, based on the current market price of reference materials (eg, corn and soybean meal). If the current market price of a potential dietary ingredient is less than the break even price, it is economically feasible to use it in the diet. If the current price exceeds the break even price, it is not a feasible economic alternative. Break even prices of ethanol coproducts can vary a great deal, depending on the prevailing market price of the reference materials. Corn (an energy source) and soybean meal (a protein source) are common reference materials in the Midwest. In Table 5 is illustrated break even prices for DDGS, CGF and CGM when corn and soybean meal are at varying prices. When corn and soybean meal are $98 and 221 per tonne, respectively, the breakeven price for DDGS is $166/tonne (Table 5). When the prices for corn and soybean meal increase to $118 and 300 per tonne, respectively, the break even price for DDGS increases to $219 per tonne. These data (Table 5) are illustrative of several points: (1) break even price changes with change in either corn (energy source) or soybean meal (protein source), (2) soybean meal price changes affect break even prices more than corn (because protein is priced higher than energy), (3) market prices of CGF and DDGS (Figure 2) rarely exceed break even prices and (4) there are wide margins between market prices of DDGS and CGF and their break even prices. In general, DDGS and CGF are marketed below theoretical optimal value.

Besides optimizing the cost of dietary ingredients, animal producers may include ethanol coproducts in diets for other reasons. One possibility is to improve diet quality. Typically, this would occur when forage quality is less than expected (low energy and/or low protein content). Adding a coproduct such as DDGS (which has high energy and protein content) will improve diet quality. Likewise, when the forage supply is marginal, producers may purchase coproducts to extend the supply of forage. It is important that diet quality not be compromised; generally, ethanol coproducts do not compromise quality. Producers may add coproducts to alter diet characteristics; an example of this would be replacement of corn with CGF to reduce the starch load in the rumen and mitigate adverse effects of low ruminal pH. Another common example is adding DDGS to reduce the degradability of production diets, due to their high energy and protein contents. Often this is done with diets containing large amounts of silages, which typically have low concentrations of ruminally undegradable protein.

Issues that affect marketing

Supply and demand

The marketing of coproducts provides an important source of revenue in ethanol production; supply and demand can have a large impact on coproduct prices and the economics of processing over long periods of time. Supply and demand can be affected by a number of factors. The price of other dietary ingredients is a major influence. Historically, market prices of coproducts have fluctuated in parallel with corn and soybean meal (Figure 2). Due to their higher protein content, coproducts typically have brought a higher price than corn. In the future, this trend may be disrupted if the amount of corn processed into ethanol continues to increase. As the amount of corn processed into ethanol increases, the supply of coproducts necessarily will increase, which will continue to put downward pressure on market value of coproducts. This appears to be the case with DDGS, which has decreased relative to the value of corn since the 1990s (Figure 2). The situation is complicated further by supply and market value of corn, soybeans and other commodities which have direct and/or indirect effects on market value of the coproducts. Thus, maintaining a viable, sustained market, while important to long term viability of ethanol plants, is a complex issue. As conventional markets for DDGS and other coproducts become saturated, additional markets will be necessary for long term sustainability.

Short term factors also can affect the market price of coproducts. One factor is storage capacity. Most dry grind ethanol plants have limited storage capacity for DDGS (approximately a week). If there is a momentary decline in demand, market prices often are reduced to create demand and reduce inventory. Limited storage capacity also can create short term shortages; if there is an unusually large demand for coproduct or if processing is disrupted for a period of time, processors may not have sufficient supply to meet all demands. If this happens, animal producers that are not able to obtain material will have to make abrupt changes in diet formulation. Abrupt dietary changes can reduce intake, animal productivity and income; producers often avoid ingredients if their supply is inconsistent. Another short term factor is momentary over supply of competing feed ingredients. For example, during the fall harvest season, the supply of whole cottonseeds can be high and the market price for whole cottonseeds can be low.

Because whole cottonseeds have some nutritional properties that are similar to those of DDGS, the low price of whole cottonseeds can depress the market value of DDGS for a short period of time. Fluctuations in the supply of corn and soybeans in either the domestic or international markets can have both short term and long term impacts on the market price of ethanol coproducts.

Variability

The chemical composition of many coproducts can vary markedly; this has been documented (Arosemena et al 1995, Belyea et al 1989, Belyea et al 2004, Shurson et al 2001). Most nutrients are affected, but protein probably is the most important because of economic and biological implications. Protein content of coproducts can vary several percentage units from batch to batch; for example, the protein content of DDGS can vary from 25 to 35% (Rausch, unpublished data; Belyea et al 2004). DDGS typically is marketed with a conservative estimate of protein content (ie, 25%) so that label specifications are attained. However, because of variation, protein content of a given batch of DDGS could be 5 to 10% units higher than the guaranteed minimum specification. Unless the purchaser analyzed the shipment of DDGS and made appropriate adjustments, diets containing DDGS would contain excess protein. It would be possible for ruminants consuming the resulting diet to consume 0.5 to 1.0 lbs of excess protein per animal per day. This results in a waste of resources and contributes to excess nitrogen in animal waste. High protein also can increase concentrations of body urea, which can have adverse physiological effects. From a marketing standpoint, it also means that about one fourth of DDGS protein is under valued and represents unrealized income. Variation in fiber and energy content is similar in magnitude to that associated with protein, with similar effects on diet quality.

Variation is not limited to protein or fiber. Concentrations of most elements also vary. Coefficients of variation ranged from 10 to 30% for many elements among coproducts (Belyea et al 1989). Clevenger et al (2004) measured element concentrations of DDGS from different dry grind plants; for many elements, the variation among plants was more than 50%. Others (Arosemena et al 1995, Shurson et al 2001) reported similar variations. Such variations can lead to adverse effects on animal health and production. Mineral imbalances are especially difficult to resolve, because adverse effects can be subtle, latent and confounded. The problem of variation in composition of coproducts is complicated by disagreement of published data with contemporary data. Several groups (Arosemena et al 1995, Belyea et al 1989, Belyea et al 2004, Clevenger et al 2004 and Shurson et al 2001) have shown contemporary analytical data for many coproducts differ substantially from published sources, such as NRC (1982). A clear explanation for the discrepancies between contemporary data and historical data is not evident, but it most likely reflects differences in processing methods and conditions. Unfortunately, many databases, especially those used to formulate diets, contain historic rather than contemporary data. This can lead to diet formulation errors.

Variability in DDGS composition from dry grind plants could be due to several reasons. DDGS is produced by the blending of two parent streams, wet grains and syrup (Figure 4). We have shown the composition of either stream can vary considerably; for example, protein content of syrup can vary from 16 to 30% (Rausch et al 2003a, 2004). Protein content of wet grains, although considerably higher than syrup, also can vary. In addition to variation in composition of the parent streams, blending of the two streams is not a precise operation. Thus, the proportion of wet grains to syrup also can vary. Because these two sources of variation could interact, it is not difficult to understand why the composition of DDGS can vary. In addition to these two sources of variation, processors sometimes market either wet grains or syrup separately, biasing the composition of the resulting DDGS.

There are no data to indicate the periodicity of variation. It is not known if variation is primarily within or among fermentation batches. If it is within batches, it may be difficult to modify processing to reduce variation, because it is related to biological events in the fermenters. If variation is among batches, at least part of the variation is due to the blending of syrup and wet grain; modifying this step may be possible from a practical standpoint. When batches of DDGS are placed in storage, it is carried from the dryers to the storage facility by conveyer. Batches are placed in sequential piles, so that batches are mixed to some extent. When shipped, adjacent piles of DDGS are removed with a front end loader, which tends to blend DDGS from several piles (batches). This tends to reduce variation, because batches become blended as they are removed for shipment. However, it is possible for a shipment of DDGS to contain portions of several original fermentation batches and to reflect the associated variation in composition. Put another way, DDGS composition can vary substantially within a shipping unit (truck or rail car). This makes diet formulation difficult.

Phosphorus content

Eutrophication is the process in which bodies of water naturally age; it is caused by presence of nutrients and is characterized by growth of algae and reduced oxygen levels. Bodies of water are classified as eutrophic if the phosphorus concentration is 31 μg P/L or higher (Clevenger 2003). High phosphorus concentration is the primary cause of eutrophication; runoff from agricultural land is a major source of phosphorus entering surface waters. Animal waste can contain 1,000,000 μg P/L; it does not take much waste to increase the phosphorus concentration of bodies of water. Reducing phosphorus in animal wastes and controlling application of animal wastes to land are needed to reduce pollution of surface waters. Many bodies of water in the US are experiencing increasing phosphorus content; recreational lakes in southwest Missouri are examples. Phosphorus concentrations of these lakes have been increasing for the past several decades; many are near eutrophic conditions. There is a large concentration of animal production facilities in this area; animal wastes are a major source of phosphorus. Some states have regulatory thresholds above which application of animal wastes is reduced or eliminated to prevent further pollution of surface waters.

Managing the phosphorus content of diets is one aspect of reducing the phosphorus in animal wastes. Phosphorus contents of most corn processing coproducts range from 5.4 to 8.2 g P/kg db, which is high relative to common grains and to requirements of most ruminants (Table 4). High phosphorus in diets can increase phosphorus in animal wastes (Morse et al 1992). Regulations for disposal of animal wastes are becoming increasingly stringent and are based, at least partially, on phosphorus content. Most ruminant diets have adequate or nearly adequate phosphorus concentrations. Adding high phosphorus ingredients to typical ruminant diets will increase dietary phosphorus concentrations and phosphorus content of wastes (Dou et al 2001, Rotz et al 2002, Spears et al 2003, Tamminga 1992, Van Horn et al 1996). High phosphorus wastes may cause disposal difficulties for some producers because land application of animal wastes is based primarily on phosphorus loading of soil. Some producers may have to forego using DDGS or CGF, because of lack of sufficient land for waste disposal.

For animals in a production setting, phosphorus excreted in wastes is considerable. A lactating cow consuming 25 kg/day of diet that contains 3 mg P/kg of diet will consume 75 g P/day. About 75% (56 g P) of the phosphorus will be recovered in animal wastes. This amounts to 4,124 kg P annually for a herd of 200 animals. Depending on soil phosphorus and crops being grown, this could require from 80 to 160 ha of land. Pasture land and land used for producing forages require less phosphorus (2.2 to 22 kg P/ha) for crop growth than grain crops, such as corn (28 kg P/ha or more; Lory 1999). This affects the amount of animal waste that can be land applied. Adding DDGS to the diet could increase the phosphorus concentration to 4 mg/kg. This would increased phosphorus excretion to about 5,600 kg P annually and require from 100 to 200 ha of land for waste disposal. Because production systems are often several times larger than 200 cows, the magnitude of the disposal problem increases significantly for larger operations. It is possible that some animal producers will not purchase dietary ingredients with high phosphorus, such as DDGS, because of lack of disposal alternatives.

Broadening market opportunities with new process technologies

Ethanol coproducts are fed primarily to ruminants; it is not clear if the ruminant market will grow any significant degree or if it is saturated. The supply of DDGS will increase considerably, because of growth in ethanol production. It seems logical that for ethanol processing plants, especially dry grind plants, to maintain economic stability it will be necessary to expand markets for coproducts. This could be achieved with modifications in processing technologies. For example, processing techniques to remove fiber from corn prior to fermentation should result in a modified DDGS that is low in fiber and high in protein. The resulting modified coproduct would be suitable for feeding to nonruminants in significant quantities. There are sizeable nonruminant industries (poultry and swine) in close proximity to dry grind plants in the upper Midwest that represent a large market potential. For example, in Minnesota, approximately 20 million hogs were marketed in 2004; approximately 45 million each of broilers and turkeys were marketed in 2003 (MASS 2004). If half these market animals were fed diets containing 10% of a modified (low fiber, high protein) DDGS, they would consume about 3,000 tons per day, or the output equivalent about 10 typical dry grind ethanol plants.

The high phosphorus concentration of conventional DDGS poses a potential market limitation for ruminants, because of implications on animal waste disposal. Technologies that reduce the phosphorus concentration of DDGS will reduce concerns regarding waste disposal. DDGS typically contains 0.70 g P/100 g db; if this could be reduced 50% (to 0.35 g/100 g db), adding large amounts of DDGS to ruminant production diets would not increase dietary phosphorus significantly and have little effect on animal waste disposal. We have shown that one dry grind processing stream (syrup) contains most of the phosphorus in dry grind processing (Rausch et al 2003a, 2004). Processing this stream (syrup) to remove a significant amount of the phosphorus would result in a modified (low phosphorus) DDGS; because phosphorus in syrup appears to be carried in the water phase, technologies that remove phosphorus also probably will remove water, solving two processing issues. In summary, the present markets for ethanol coproducts (ruminants) probably is not going to grow substantially in the near future and, in fact, could shrink, if animal waste disposal becomes more strictly regulated. New technologies to remove phosphorus could help sustain this market; if techniques could be perfected to remove fiber, the resulting modified DDGS could be used in nonruminant diets, opening up a new, large market segment.

An additional processing challenge: water removal

Need for water removal

Coproduct streams from corn processes are large in volume, relatively low in total solids (<20%) and contain valuable nutrients. While some coproducts can be marketed locally without drying, most are dried to increase transportation efficiency and to avoid deterioration of material. To reduce energy costs, processors market a fraction of their coproducts as wet animal food ingredients (syrup, wet grains, heavy steepwater). Due to the perishable nature of the wet ingredients and shipping costs, selling of wet ingredients is limited to a relatively small area surrounding a plant. Extending the marketing area for wet material increases risk of microbial growth, leading to risk of mycotoxin production.

Removal of water from corn processing streams is costly in terms of energy and involves use of equipment that contribute to capital and operating expenses. Alternative methods that use less would have an advantage in wet milling and dry grind processes. Coproduct streams must be reduced to a solids level of 90% to ensure safe transportation and storage for periods longer than 48 to 72 hr. CGF, CGM and DDGS are marketed on a 88 to 90% solids basis. Light steepwater, light gluten and thin stillage streams have 7 to 11, 4 to 6 and 5 to 10% solids, respectively (Table 1).

A secondary reason for water removal from coproduct streams is diet formulation. Most coproducts are mixed with other animal food ingredients to form complete nutritional diets. Water content of coproducts affects their ability to mix with other animal diet ingredients. Higher water content typically makes uniform mixing more difficult and time consuming.

Methods of water removal

Removal of water is achieved by dewatering unit operations, such as pressing, filtering or centrifugation, followed by drying or evaporation. Two notable exceptions are light steepwater and thin stillage, which are concentrated by evaporation, mixed with a carrier (fiber and wet grains, respectively) and dried. Dewatering operations use far less energy than drying methods since a phase change of water is not involved (Table 6). In the wet milling process, screw presses used for germ and fiber dewatering can remove water to 50% solids. Remaining water is removed in rotary drum dryers. Light gluten (4 to 6% solids) is concentrated to form heavy gluten (10 to 14% solids) using a centrifuge, followed by vacuum belt filtration to increase solids to 40% before drying in ring dryers to 90% solids. Steepwater is concentrated by evaporation to 45% solids, mixed with fiber and dried in a rotary drum dryer. In the dry grind process, syrup (condensed distillers solubles) is produced from concentrating thin stillage (5 to 10% solids) by evaporation to 35% solids. DDGS is formed by mixing syrup with wet grains and drying to 90% solids (Figure 4).

Membrane filtration is a new method used for removal of water in corn processing streams. Membranes can improve process efficiency since their separations can result in water suitable for recycling within the processing facility (Cicuttini et al 1983, Kollacks and Rekers 1988, Rausch 2002). Membranes use smaller amounts of energy relative to evaporation and drying operations (Table 6) but tend to add complexity to overall processes and must be evaluated with respect to durability and cleaning costs. Membrane technologies have been used in front of evaporative unit operations in other industries (eg, dairy) but are not used widely in the corn processing industry (Rausch 2002).

Costs of removing water in commercial corn processes are significant and the ability to remove water using dewatering technologies would have an important impact on energy costs. Commercial dewatering equipment requires 1.2 to 23 kJ/kg water removed from the coproduct stream. In contrast, drying requires inputs of 700 to 3,700 kJ/kg water removed from the coproduct, an energy input increase of two orders of magnitude (Table 6). As a general rule, the initial 90% of water to be removed by dewatering requires approximately 5% of the energy input; the remaining 10% of water to be removed by drying requires 95% of the total energy input to increase solids content from 10 to 90%.

Ethanol processes face some difficult challenges if they are to improve competitiveness, profitability and sustainability while reducing coproduct variability and energy costs. For example, the processor faces additional challenges if coproducts are to be marketed as ingredients in poultry diets. The turkey production industry has a lower tolerance for variation in composition than the ruminant animal industry. With uncertain energy costs, water removal will have an increasingly important role for corn processors to consider.

New Technologies to Modify the Dry Grind Process

Rationale for modifying the dry grind process

Processes used to produce ethanol have different equipment and techniques, which result in a divergent array of processing streams, primary products and coproducts. A brief summary of each process and their primary products and coproducts is presented in Table 2. The data in this table as well as preceding discussion make it clear that, compared to other processes, the dry grind process is at a distinct disadvantage in terms of variety of primary products and coproducts that can be marketed.

For each process, relative quantities of primary products and coproducts and their market values are presented in Table 3. Ethanol yields have a range of 7% for the different processes (750 to 805 L/tonne corn). However, quantities and values of coproducts vary. The dry grind process yields 286 kg/tonne of DDGS (worth $115.10/tonne, based on ERS data from 1994 to 2004) or total income of $30.85/tonne corn. Other processes have higher market incomes, because of the variety of materials produced and higher market value. These data are illustrative of the competitiveness among ethanol processing industries; lack of a diversity of marketable and valuable coproducts make dry grind processing more vulnerable to marketing issues. To broaden markets for coproducts, there is a need to separate germ and fiber from other corn components, allowing their use in nonruminant diets. This modification to the dry grind process could expand market opportunities and increase the long term economic sustainability of dry grind processing. The modified dry grind processes described below, proven at experimental scale, provide opportunities to improve coproduct marketability.

Modifications to the dry grind process

New processes have been developed to address the issue of coproduct value. In modified dry grind corn processes called quick germ (QG), quick germ quick fiber

(QGQF) and enzymatic dry grind, whole corn is soaked in water and lightly ground in a conventional disk attrition mill (Figure 6; Singh et al 2005). Enzymes are incubated with the ground slurry in each process to increase the specific gravity prior to germ and/or fiber separation. These processes offer varying levels of sophistication, initial capital investment and potential coproduct value. In the QG process, only germ is recovered; in QGQF, germ and pericarp fiber are recovered; in enzymatic dry grind, germ, pericarp fiber and endosperm fiber are recovered.

These processes separate germ (Singh and Eckhoff 1996, 1997), pericarp fiber (Singh et al 2000, Wahjudi et al 2000) and endosperm fiber (Singh et al 2005) using principles of density difference, hydrodynamics and particle size. Using conventional hydrocyclone systems used in the wet milling industry, germ and pericarp fiber can be recovered. Using wedge bar screening systems, endosperm fiber can be removed. Thus, established process methodologies from wet milling and conventional dry grind processes were joined to obtain more and higher valued coproducts concurrently with ethanol production.

Quick germ (QG) process

The QG process involves soaking whole corn in water for 3 to 12 hr before wet processing (Singh and Eckhoff 1996, 1997). Soaking of whole kernels results in differential swelling of corn components which loosens the attachment of the various grain components to one another. After soaking, a conventional disk attrition mill is used for degermination, as used in wet milling. The ground slurry is incubated with amylase enzymes (Figure 6) for 3 hr which increases the slurry specific gravity. The adjusted specific gravity allows germ to be recovered by hydrocyclones. The QG process has been shown to be an economical modification to the conventional dry grind process, requiring $7 million for a 1,000 tonne/day (40,000 bu/day) corn processing facility (Singh and Eckhoff 1997).

Recovery of germ as a coproduct creates options and economic opportunities for the dry grind corn processor. Based on historical data for 1994 to 2004, crude corn oil from germ had an average value of $522/tonne compared to $115/tonne for DDGS during the same period (ERS 2005). Recovery of germ allows additional processing of the germ to extract corn oil which has many higher value uses. Additionally, there are cost savings associated with increased fermenter capacity due to removal of nonfermentables from the corn mash and due to reduced fouling of the thin stillage evaporators (Singh and Eckhoff 1997, Singh et al 1999a, Taylor et al 2001a). The QG process is a straightforward process methodology to enhance economic sustainability of ethanol production facilities.

Quick germ quick fiber (QGQF) process

In the QGQF process, germ and fiber are recovered together in a process similar to the QG process. Corn is soaked, ground in a disk attrition mill and incubated with amylase (Figure 6). Soaking and incubation parameters are adjusted so the specific gravity of the slurry causes flotation of the pericarp fiber with the germ. Using hydrocyclones, germ and fiber are separated from the other corn components. With an aspiration step, recovered germ and pericarp fiber are separated following drying (Singh et al 1999a, Wahjudi et al 2000).

Recovery of pericarp fiber has several advantages compared to the conventional dry grind corn process. It increases fermenter capacity 6 to 8%; increased fermenter capacity is one of the major economic incentives for implementing the process, in addition to improved coproduct value. Pericarp fiber concentration in DDGS is reduced and potential for including DDGS in nonruminant livestock diets is enhanced (Singh et al 2005).

In comparison to other cereal grains, high levels of cholesterol lowering phytosterol components, ferulate phytosterol esters, free phytosterol and phytosterol fatty acyl esters, can be extracted from pericarp fiber (Singh et al 1999a). Compared with other cholesterol lowering edible oil supplements, corn fiber oil extracted from corn fiber contains high amounts of these phytosterol compounds relative to other grain fibers (Moreau et al 1999). These cholesterol lowering compounds can be used as nutraceuticals and command a high market value.

Due to germ and fiber removal, nonfermentable solids in the fermenter are reduced, increasing material that can be processed through the fermenter. Savings for using the germ and fiber removal process over the conventional dry grind corn process were estimated at 1.3 to 1.8 cents/L ethanol (5 to 7 cents/gal; Taylor et al 2001a). Costs of retrofitting a 1,000 tonne/day (40,000 bu/day) corn processing plant with germ and fiber removal technology were estimated at $9 million. The resulting DDGS was higher in protein and lower in fiber contents than conventional DG and the improved QG processes. With removal of germ and pericarp fiber, QGQF moves a step beyond the QG process and further increases the potential economic sustainability of corn dry grind facilities.

Enzymatic dry grind process

A further modification to the dry grind process was to add a protease during the incubation step of QGQF. In the enzymatic dry grind process, protease is added along with amylase (Figure 6), allowing endosperm fiber removal using a sieving step. When this was used, the endosperm matrix was altered so that endosperm fiber was recovered using a sieving step (Johnston and Singh 2001, 2004). Removal of endosperm fiber, in addition to germ and pericarp fiber removal, increased protein and decreased fiber contents of DDGS from enzymatic dry grind (Singh et al 2005).

Additional costs of retrofitting a 40,000 bu/day (1,000 tonne/day) dry grind corn processing plant with the enzymatic dry grind process were estimated at $2 million, or $11 million additional cost relative to a conventional dry grind facility of similar capacity. Enhancements made with enzymatic dry grind require a minimal additional investment relative to QGQF, but result in a DDGS that has nutrient composition approaching those of CGM and soybean meal.

Effect of process modification on coproduct value

DDGS produced by the modified dry grind processes is changed from DDGS produced by the conventional dry grind process (Singh et al 2005). Relative to the conventional dry grind process, protein content of DDGS is increased from 28 to 36, 49 and 58% protein (db) for QG, QGQF and enzymatic dry grind processes, respectively (Table 7). Break even prices of DDGS are increased from $150/tonne for the conventional dry grind process to $176, 209 and 238 per tonne for QG, QGQF and enzymatic dry grind processes, respectively, using methods to estimate nutritional value (Howard and Shaver 1997).

Germ fractions recovered from QG, QGQF and enzymatic dry grind processes are of a quality that can be used for oil extraction and contain 35 to 40% oil (db), similar to oil content found in germ recovered using wet milling. The value of germ recovered by the modified dry grind processes is estimated to be $260 to 266 per tonne (Table 7); Johnston et al 2005); no germ is recovered in the conventional dry grind process.

The method to recover germ from various processes has been shown to change composition of the germ, especially crude fat (oil) content (Table 8, Johnston et al 2005). This ability to recover high purity germ alleviates a problem with germ recovered by other processes, such as dry milling. Because oil extraction is a capital intensive process, economy of scale for extraction facilities is large. A germ coproduct that does not contain high oil concentrations (ie, 35 to 40% db oil) will not be accepted at large extraction facilities, reducing the market value of the lower purity coproduct. In the wet milling process, germ recovered will have a value of $218 to 247 per tonne. In dry milling, recovered germ will be worth $128 to 150 per tonne, which is similar to the value of DDGS in the conventional dry grind process ($115/tonne). Therefore, there is little economic incentive for dry grind processors to recover germ using a dry milling germ recovery technique. Recovery of high quality germ as a coproduct is a distinct and important objective of modified dry grind corn processes.

Modification of the dry grind process affects the economics of plant construction and process efficiency. While overall capital costs are higher for modified dry grind processes (eg, $0.38, 0.40 and 0.42 per L annual ethanol capacity for QG, QGQF and enzymatic dry grind, respectively) compared to conventional dry grind (eg, $0.33/L annual ethanol capacity). These estimates are for capital investment only and do not reflect the increased revenue from higher coproduct values for modified dry grind processes; they are less than capital investment required for corn wet milling ($0.62 to 0.92 per L annual ethanol capacity; Johnson and May 2003). Lower capital investment allows smaller processing facilities to be built and operated economically in regions where corn supply is plentiful.

Membrane filtration for water removal and coproduct improvement

The processes described earlier show potential for improved coproduct quality and value when producing ethanol. However, these process designs do not address the challenge of removing water from coproduct streams. Conventional dry grind processing removes water to produce DDGS by use of evaporation and drying; it does not remove water from coproduct streams by pressing, centrifugation or filtration. There is great potential to reduce energy use by implementing membrane filtration technologies within ethanol processing facilities.

Relatively few researchers have shown the effectiveness of membrane filtration in modern fuel ethanol plants. Some have studied removal of water and reduction of wastewater strength (Wu 1988a,b, Wu and Sexson 1985, Wu et al 1983) but this work was done before the latest ethanol processing facilities came into production and before the latest advances in membrane materials were available. We evaluated the effectiveness of laboratory scale microfiltration systems to remove water from wet mill processing streams (Templin et al 2005, Thompson et al 2005) and showed the potential of microfiltration to remove considerable amounts of water (and elements). Templin et al (2005) found that microfiltration of light gluten recovered 67% of total ash in the permeate stream and nearly 80% of protein in the retentate stream, while solids were concentrated nearly six fold in simple batch filtration experiments. In larger scale membrane filtration work (Thompson et al 2005), light gluten separation achieved a nearly five fold increase in total solids in membrane concentrate while permeate concentrations of total ash were five times higher than in the original light gluten stream. Ability to remove ash (phosphorus) from coproduct streams as well as requiring small amounts of energy for dewatering (Table 6) illustrate the potential for broader use of this technology in corn processes.

High phosphorus content in corn processing coproducts represents an important environmental issue. One of the challenges to affecting reduced phosphorus content is a lack of understanding of the flow of phosphorus in corn processes. Many corn processors are unaware of the phosphorus concentrations in various streams of their process and therefore unable to identify opportunities for changing phosphorus content in final coproducts. Several processors have indicated they know more about nutrients flowing into the waste treatment facility than into their coproducts.

We conducted a series of experiments to determine which streams carry most of the phosphorus in wet milling and dry grind processing and to evaluate effectiveness of microfiltration to remove elements. Steepwater streams in wet milling and the syrup stream in dry grind accounted for much of the phosphorus flowing in each process (Rausch et al 2005; Rausch et al 2003a). We used a laboratory scale microfiltration system to process steepwater and gluten streams from a wet milling plant. This system effectively reduced ash content of light steepwater and light gluten (data not shown); more work is needed to determine phosphorus removal using of membrane filtration.

Conclusions

Coproducts are an inherent part of corn processing and historically have not received the same attention in development as primary products. As a result, these coproducts have chronic low value and high processing costs and typically are marketed as animal food ingredients, especially for ruminant diets. Growth in corn processing, due to recent increases in ethanol production, has caused a proportional growth in coproduct output.

Several factors have placed pressure on the value of coproducts, including issues of supply and demand, compositional variation, nutritional value for ruminant and nonruminant animal diets and environmental issues raised with adding coproducts to animal diets. Additional issues facing the processor include the cost of producing coproducts so they can be handled and stored safely and efficiently and increased awareness of the consequences of high phosphorus content. For long term profitability and sustainability, processors and the corn processing industry as a whole need to identify and develop technologies that will address these issues. Some advancements have been made to improve processing methods that enhance coproduct value and improve economic feasibility of ethanol production in rural communities. With rapid changes in the ethanol industry expected in the next 5 to 10 years, additional work is needed to develop proactively ethanol production methodologies that mutually meet economic, nutritional and environmental concerns.

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Table 1. Composition (g/100 g db) of main processing streams and coproducts from ethanol processes.

Process	Coproduct	Solids (g/100 g)*	Protein[1]	Crude Fiber	NDF	Fat	Ash	NFE
Wet milling[2]	Light steepwater	10.5	46	--	--	--	16	38
	Fiber	--	9	10	0	6	2	73
	CGF	10.0	23.8	8.9	35.5	3.5	6.8	55.7
	Germ meal	10.0	26	--	4	2	5	56
	Light gluten	4.5	69	1	--	2	2	26
	CGM	10.0	65	1.3	11.1	2.5	3.3	25
	Distillers solubles[9]	4.41	22.4	--	--	12.1	11.1	--
Dry grind	Beer[8]	11.9	29.8	--	--	--	--	--
	Thin stillage	7.1	33.4	--	--	--	--	--
	Wet grains	32.8	33.4	13.8	43.2	7.6	2.2	0.43
	Syrup	27.5	29.8	4.2	22	9.4	7.3	1.12
	DDGS[10]	84.3	29.6	4.2	--	9	--	--
Dry milling	Hominy feed[7]	13.5	11.9	6.7		4.2	2.7	0.65
	Flaking grits[6]	13.8	8.7	0.3	--	0.5	0.2	90.3
	Brewers grits[6]	11.7	8.7	0.5	--	0.8	0.3	91.9
	Corn meal[6]	12.0	8.0	0.6	--	0.8	0.5	92.1
	Corn cones[6]	11.5	9.0	0.5	--	0.7	0.3	91.9
	Flour[6]	12.0	6.8	0.7	--	2.5	0.7	91.5
	Germ[7]	9.6	17.5	6.3		26.3	7.4	38.4
	Bran[7]	10.0	3.8	17.2	--	1.0	1.0	--

*Solids data for dry grind (beer, wet grains, syrup, DDGS): Rausch et al (2003a); light steepwater and light gluten from Rausch et al (2003b).
[1]N × 6.25.
[2]Loy and Wright (2003).
[3]Corn gluten feed.
[4]Corn gluten meal.
[6]Duensing et al (2003); NFE column determined as “starch by difference”.
[7]Alexander (1987).
[8]Rausch et al (2003a).
[9]Belyea et al (1998).
[10]Maisch (2003).

Table 2. Summary of ethanol processes, primary products and coproducts.

Process	Brief Description	Primary product(s)	Coproducts
Wet milling	Corn is steeped, lightly ground, germ removed, finely ground, fiber removed, protein separated from starch, starch further processed. Results in a 99.5% pure starch product.	starch, ethanol, high fructose corn syrup	corn oil, corn gluten feed, corn gluten meal, carbon dioxide
Dry grind	Corn is ground, cooked, liquefied, saccharified; fermented and distilled for manufacture of ethanol.	ethanol	DDGS*, carbon dioxide
Modified dry grind	Corn is soaked, lightly ground, germ and fiber removed, finely ground, cooked, liquefied, saccharified; fermented and distilled for manufacture of ethanol.	ethanol	DDGS, germ (corn oil), fiber (nutraceuticals), carbon dioxide
Dry milling	Small amount of water added to corn, kernel is abraded to separate components of pericarp, germ and endosperm. Remaining process is primarily physical size separation.	flaking grits	brewers grits, small grits, corn meal and cones, corn flour

*Distillers dried grains with solubles.

Table 3 Comparison of typical coproduct yields and historic values for ethanol processes.

Process	Typical Coproduct Yields (per bu corn)	(per tonne corn)	Value* ($/tonne)	($/ton)
Wet milling[1]	2.5 gal ethanol	750 L	$0.34/L	$1.30/gal
	or			
	31.5 lb. starch	562.6 kg		
	or			
	33.0 lb. sweetener	589.4 kg		
	and			
	1.5 lb. corn oil	26.8 kg	521.60	474.18
	and			
	3.0 lb. corn gluten meal	53.6 kg	269.73	269.75
	and			
	12.4 lb. corn gluten feed	221.5 kg	82.93	75.38
Dry grind	2.7 gal ethanol	805 L		
	and			
	16 lb. DDGS**	286 kg	115.10	104.64
Modified dry grind[2]	2.5 gal. ethanol	750 L		
	and			
	3.4 lb. germ	60.7 kg		
	and			
	3.8 lb. fiber	67.9 kg		
	and			
	7.8 lb. modified DDGS	139.3 kg		
Dry milling[4]	flaking grits	120 kg		
	brewers grits	380 kg	264	240
	corn meal	60 kg	346	314
	hominy feed	350 kg	86	79
Corn			92	84
SBM 44			198	180
SBM 50			210	191

*ERS (2005); based on data available from 1994 to 2004.
**Distillers dried grains with solubles; yield ranges 15 to 17 lb/bu.
[1]Wet milling yields from Johnson and May (2003).
[2]Modified dry grind yields from Singh et al (2005).
[3]Dry milling yields from Brekke (1970).

Table 4. Comparison of the nutrient profile of ethanol coproducts to that of corn (NRC 1980).

Item[1]		Corn	CGM	CGF	Germ Meal (db)	DDGS	Hominy Feed	Syrup	Wet Grains
Protein	(g/100 g)	10.9	67.2	25.6	22.3	25.0	11.5	19.7	33.4
EE		4.3	2.4	2.4	4.1	10.3	7.7	--	--
Ash		1.5	1.8	7.5	4.2	4.8	3.1	--	--
CW		9.0	14.0	--	--	44.0	55.0	--	--
LC		3.0	5.0	--	--	18.0	13.0	--	--
C Fiber		2.9	2.2	9.7	13.1	9.9	6.7	--	--
Ca		0.03	0.16	0.36	0.04	0.15	0.05	0.45	0.018
K		0.37	0.03	0.64	0.31	0.44	0.65	2.32	0.54
Mg		0.14	0.06	0.36	0.34	0.18	0.26	0.69	0.18
Na		0.03	0.10	1.05	0.08	0.57	0.09	0.23	0.045
P		0.29	0.50	0.82	0.34	0.71	0.57	1.52	0.54
S		0.12	0.39	0.23	0.33	0.33	0.03	0.74	0.50
Zn	(mg/kg)	14.0	190.0	72.0	114.0	--	3.0	126	105
Essential Amino Acids (g/100 g)									
	Arg	0.54	0.87	2.31	1.4	1.05	0.62		
	His	0.25	0.68	1.55	0.8	0.70	0.31		
	Ile	0.39	0.98	2.82	0.8	1.52	0.40		
	Leu	1.12	2.44	11.33	2.0	2.43	1.09		
	Lys	0.24	0.71	1.12	1.0	0.77	0.42		
	Met	0.21	0.41	1.98	0.7	0.54	0.20		
	Phe	0.49	0.90	4.45	1.0	1.64	0.48		
	Ser	0.53	0.94	3.71	1.1	1.42	---		
	Thr	0.39	0.87	2.46	0.2	1.01	0.44		
	Try	0.09	0.17	0.33	0.22	0.19	0.13		
	Tyr	0.43	0.81	3.54	0.8	0.76	0.44		
	Val	0.51	1.22	3.43	1.3	1.63	0.58		

[1]Composition data for syrup and wet grains from unpublished data.

EE = ether extract; CW = cell wall material; LC = lignocellulose

Table 5. Equivalent nutrient value of ethanol coproducts for various corn and soybean meal prices (BFBB 2003).

Corn		SBM		DDGS		CGF		CGM	
($/bu)	($/tonne)	($/ton)	($/tonne)	($/ton)	($/tonne)	($/ton)	($/tonne)	($/ton)	($/tonne)
2.50	98	200	220	157	173	133	146	246	271
3.00	118	200	220	165	182	148	163	242	266
4.00	158	200	220	180	198	178	196	232	255
2.50	98	300	330	211	232	156	172	376	414
3.00	118	300	330	218	240	171	188	372	409
4.00	158	300	330	234	257	200	220	362	398
2.50	98	400	440	264	290	178	196	507	558
3.00	118	400	440	272	299	193	212	502	552
4.00	158	400	440	288	317	223	245	493	542

Table 6. Energy requirements to remove water from coproducts.

	Energy input (Btu/lb_{H2O})	(kJ/kg_{H2O})	Ref.
Theoretical	972	2,260	
Filtration, Membrane			
Microfiltration	3	7	6
Ultrafiltration	4	9	6
Reverse osmosis	47	110	1
Filtration, Vacuum Belt	10	23	7
Pressing			
Germ press	0.5	1.2	7
Fiber press	3	7	7
Centrifugation			
Gluten thickener centrifuge	2 – 3	4 – 7	7
Stillage (decanter) centrifuge			
Evaporation			
Single effect	1160	2700	1
Triple effect	559	1300	1
Mechanical vapor recompression	300	700	1
Drying			
Dryer	1720	4,000	1
Direct heated pneumatic dryer (ring, rotary, fluid bed), partial gas recycle	1150 – 1400	2675 – 3257	3
Indirect rotary steam tube dryer, not including steam generation efficiency	1350 – 1500	3141 – 3490	3
Indirect heat pneumatic dryer with recuperative heat exchanger	1100 – 1150	2559 – 2675	3
Indirect rotary steam tube dryer for germ	1400	3257	3
Fluidized bed dryer for corn germ	1522	3541	2
Fluid bed dryer for corn germ	1300	3024	3
Rotary dryer for corn fiber	1588	3694	2
Rotary dryer for fiber and DDGS	1300	3024	3
Rotary drum dryer, direct fired	1350	3140	5
Ring dryer for corn gluten feed	1571	3655	2
Ring dryer for DDGS	1170	2722	3
Ring dryer for gluten and fiber	1250 – 1300	2908 – 3024	3
Ring dryer for starch, maltodextrin, dextrose, etc. (open cycle)	1600 – 2000	3722 – 4653	3
Spray dryer	2153	5009	4
Spin flash dryer	2047	4762	4

1. Cicuttini et al (1983)
2. McAloon, A. 2004. Personal communication. August 31.
3. Crankshaw, C. 2004. Personal communication. September 1.
4. APV Dryer Handbook. p. 57.
5. Meredith (2003)
6. Wittwer, S. 2004. Personal communication. September 17.
7. Wideman, J. 2005. Personal communication. March 3.
8. Merediz, T. 2004. Personal communication. September 22.

Table 7. DDGS composition (% db, Singh et al 2004) and coproduct values for conventional, QG, QGQF, E-Mill dry grind processes.[a]

Composition	Dry Grind	QG	QGQF	E-Mill	CGM	SBM
Crude Protein	28.5 D	35.9 C	49.3 B	58.5 A	66.7	53.9
Crude Fat	12.7 A	4.8 B	3.9 B	4.5 B	2.8	1.1
Ash	3.6 AB	4.1 A	4.1 A	3.2 B	--	--
Acid Detergent Fiber	10.8 A	8.2 B	6.8 C	2.0 D	6.9	6.0
Coproduct Value						
Germ value[b] ($/ton)	--	236		242		
($/tonne)		260		266		
DDGS value[c] ($/ton)	136	160	190	216	238	202
($/tonne)	150	176	209	274	262	222

[a]Mean yields followed by the same letter in a row are not significantly different at a 95% confidence level.

[b]Market value based on estimates from Johnston et al (2005); see Table 8.

[c]Break even prices based on historical market values (1994-2004) of corn ($83.92/ton or $92.31/tonne), 50% soybean meal ($191.16/ton or $210.28/tonne) and calculations from BFBB (2003) and Howard and Shaver (1997).

Table 8. Composition, yield and value of germ derived from laboratory and commercial corn processes (Johnston et al 2005).

Milling Process	**Oil** (%w/w)	**Protein** (%w/w)	**Starch** (%w/w)	**Ash** (%w/w)	**Yield** (% corn dry wt)	**Germ Value** ($/lb germ)	($/tonne)
Conventional wet milling A	40.9	14.0	8.0	2.2	7.5	0.112	247
Conventional wet milling B	36.4	13.1	6.9	1.4	7.5	0.099	218
Laboratory wet milling: 24 hr SO_2 steep	38.8	18.4	11.6	2.3	7.5	0.113	249
Quick Germ: 12 hr water soak	36.4	21.4	6.2	--	6.5	0.111	245
Commercial dry milling	23.0	15.4	19.8	--	12.0	0.068	150
Ground whole corn	4.0	8.1	69.5	1.6	100		

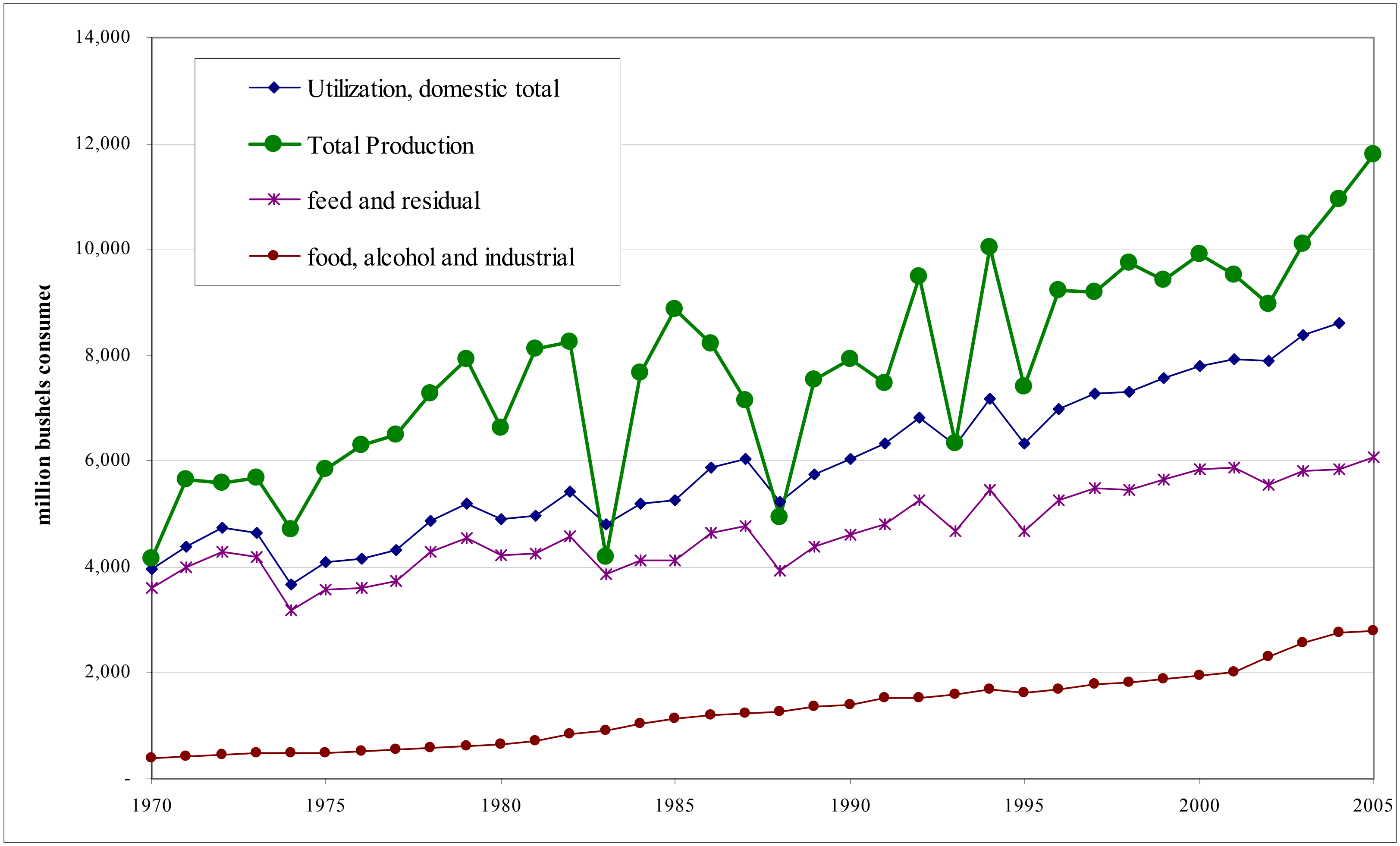

Figure 1. Production and utilization of US corn (ERS 2005).

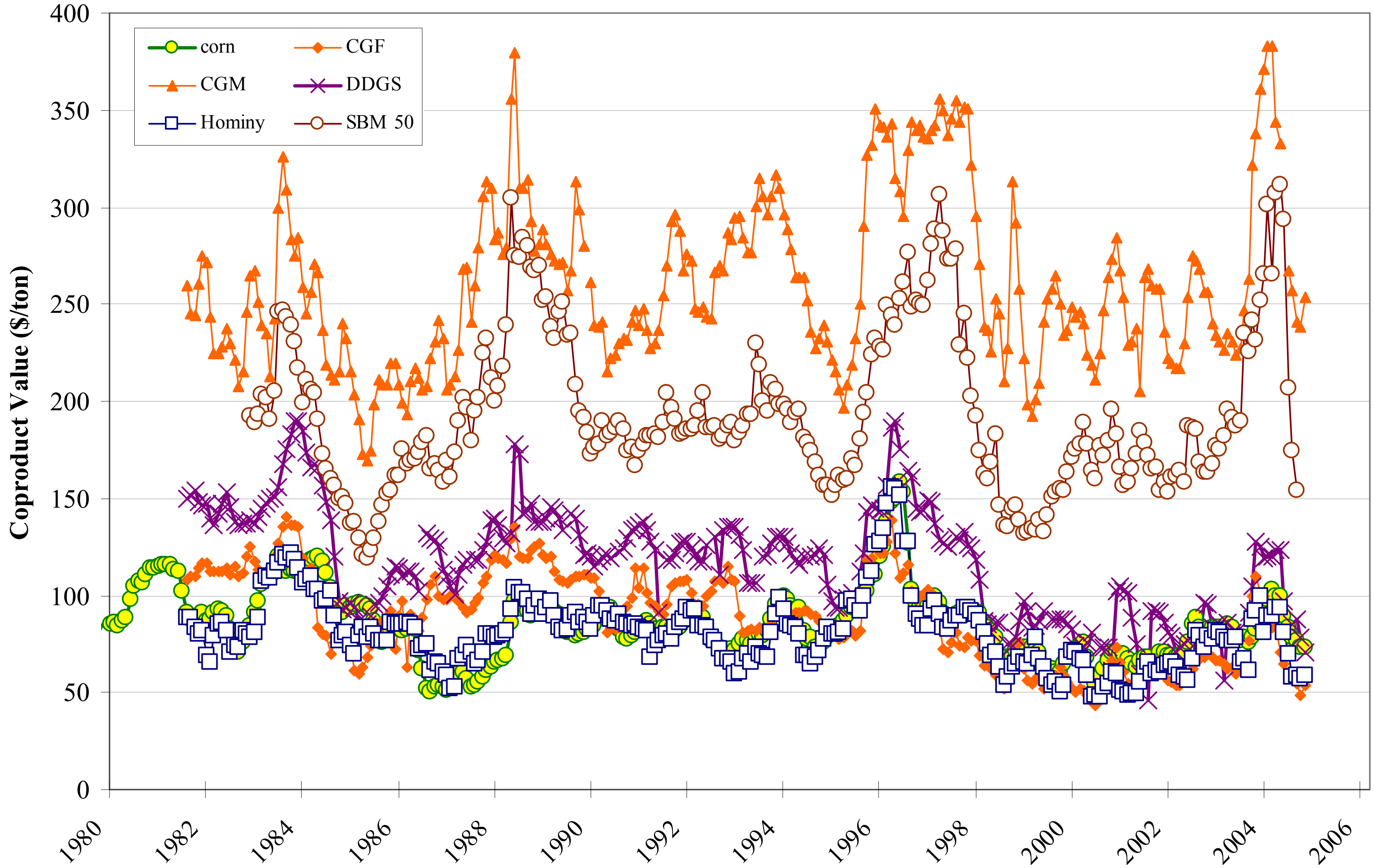

Figure 2. Price of coproducts from corn processing (ERS 2005).

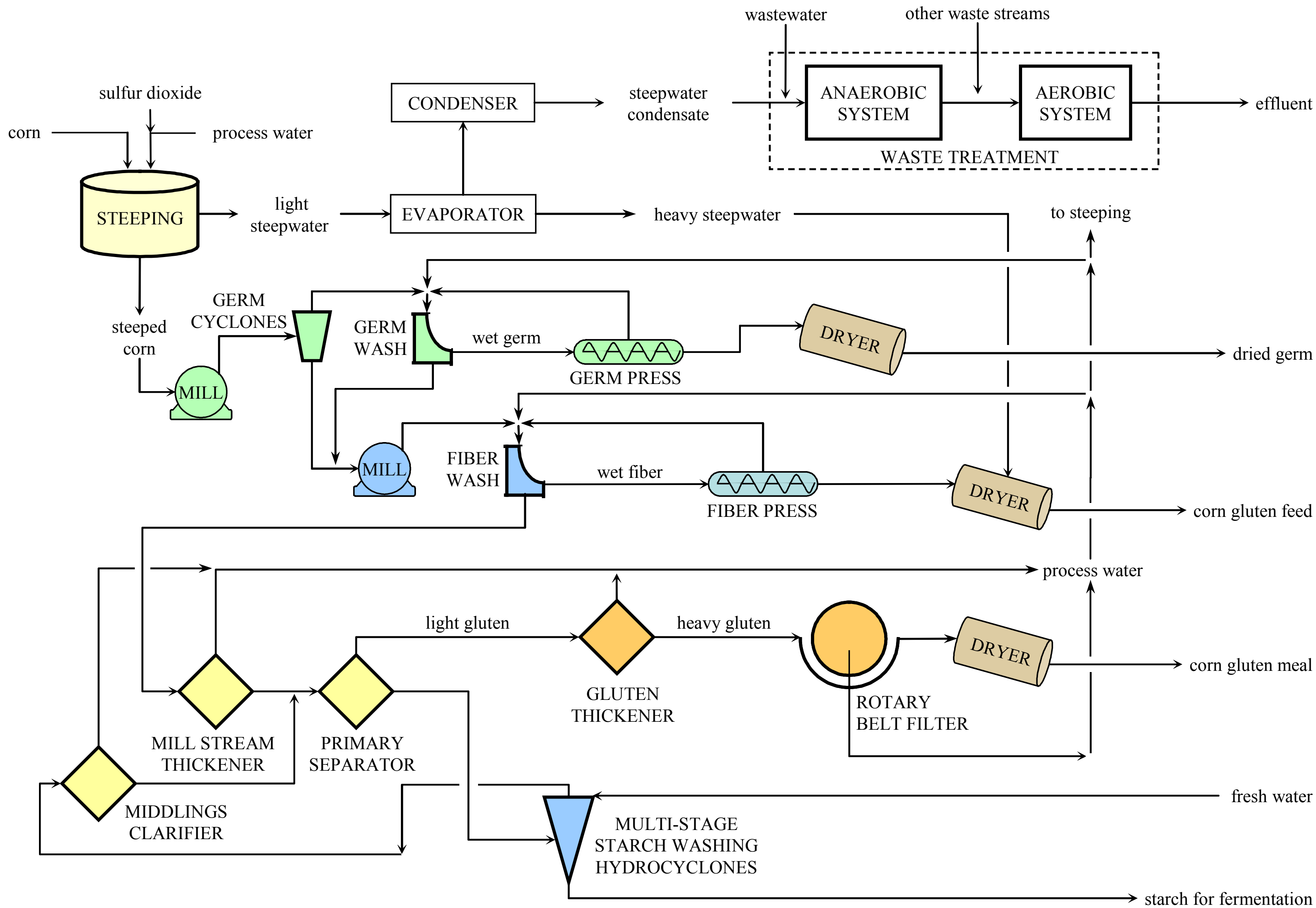

Figure 3. The corn wet milling process.

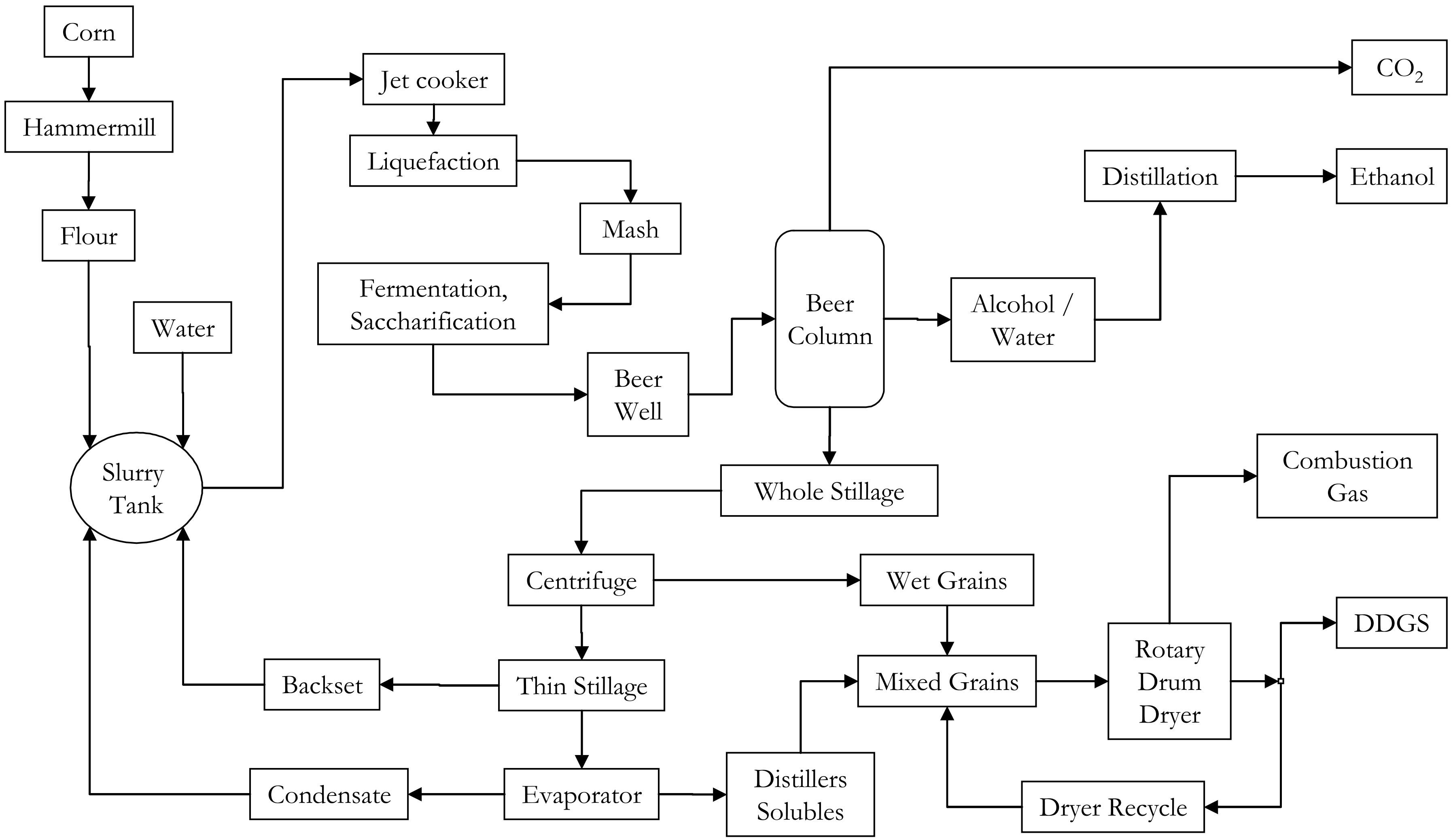

Figure 4. The dry grind corn process.

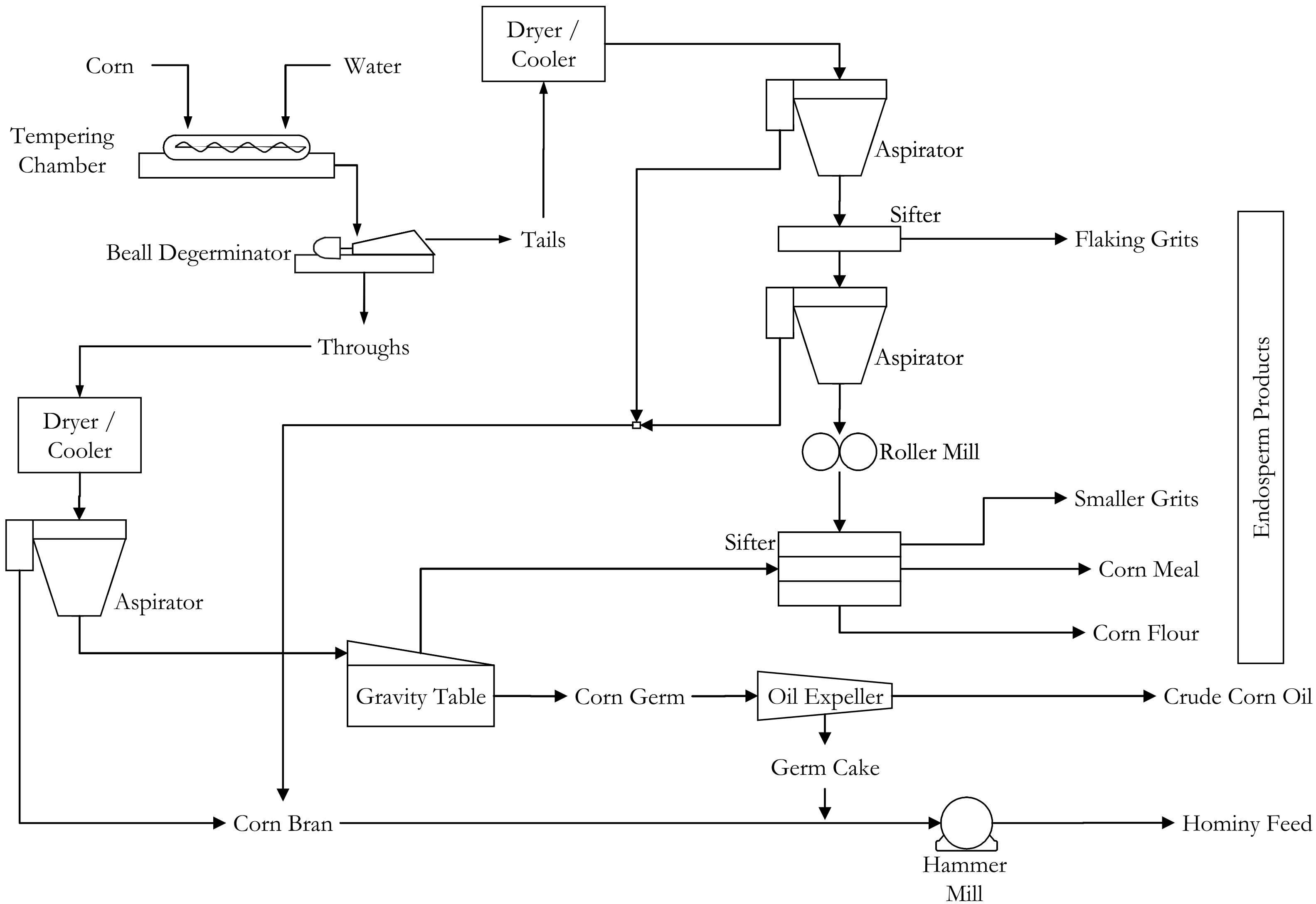

Figure 5. The corn dry milling process.

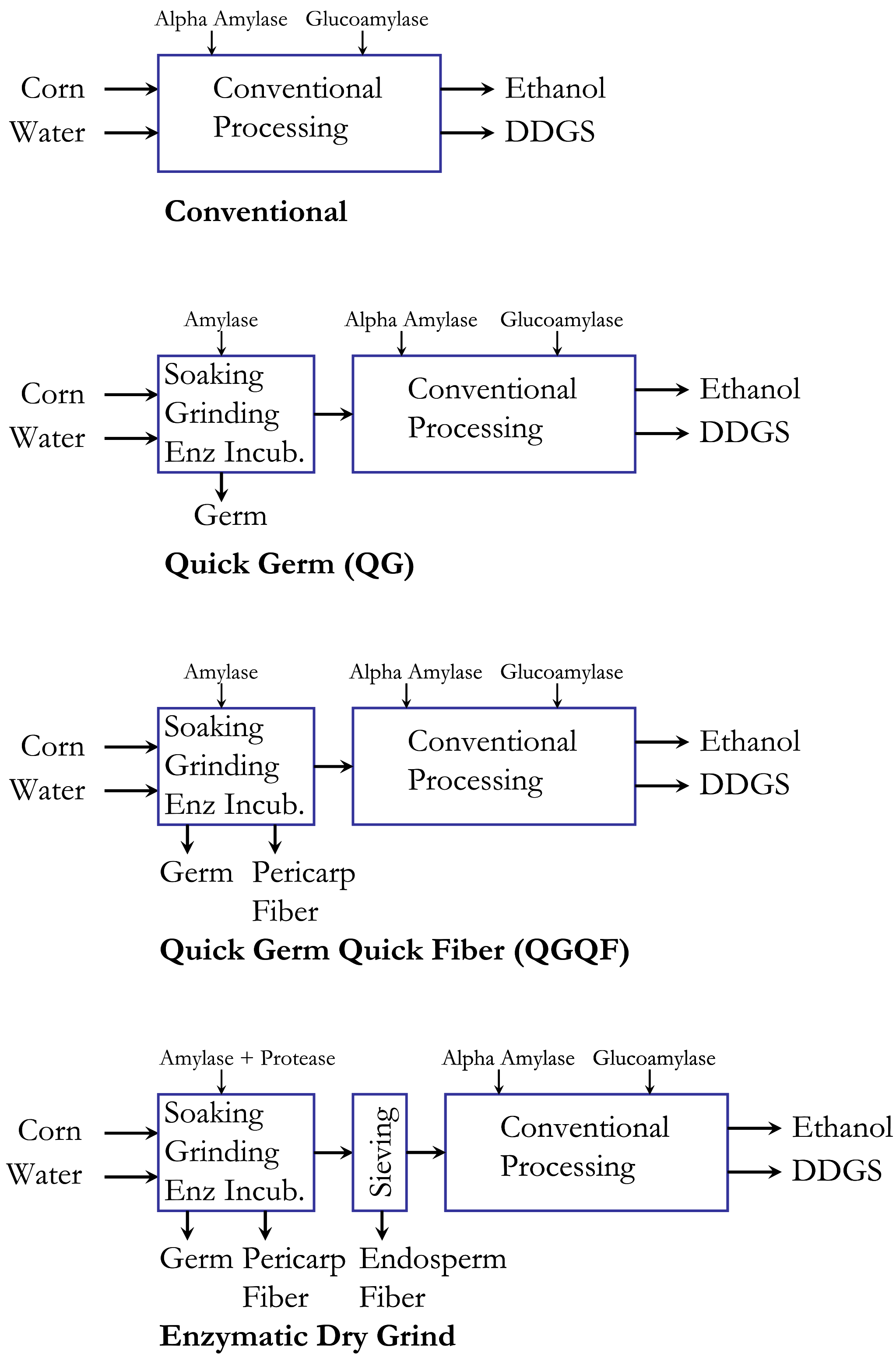

Figure 6. Modified dry grind corn processes (Singh et al 2005).