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The Future of Coproducts From Corn Processing

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Abstract

Increased demand for ethanol as a fuel additive has resulted in dramatic growth in ethanol production. Ethanol is produced from corn by either wet milling or dry-grind processing. In wet milling, the corn kernel is fractionated into different components, resulting in several coproducts. Wet-milling plants are capital intensive because of equipment requirements; they produce large volumes of ethanol and are corporate owned. In dry-grind processing, the corn 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. Several issues could affect DDGS marketing. The increasing volume of DDGS accompanying ethanol production could reduce market value; high phosphorous content could limit the 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. The development of more efficient methods of water removal would increase the efficiency of ethanol processing and reduce the costs of processing. New technologies could contribute to greater stability of dry-grind plants.

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Index Entries: Distillers' dried grains with solubles; dry-grind process; wet milling; dry milling; ruminants; pericarp; endosperm.

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 CO and other pollutants. The amount of corn used for ethanol production has increased 17-fold during the past 20 yr, to more than 600 million bu/yr (Fig. 1); in 2004, ethanol production was 3 billion gal/yr *(1)*. Much of the fuel ethanol production capacity in the United States 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 10 yr, dry-grind capacity has increased rapidly and now accounts for 70% of ethanol production *(1)*.

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 their high protein content; however, they also have high fiber content, which limits their 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 (i.e., corn and soybean meal). However, there has been a general downward trend in the market price of DDGS during the past two decades (Fig. 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. *(3–5)* 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 coproducts. The marketing of coproducts is important as a source of income to offset the 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

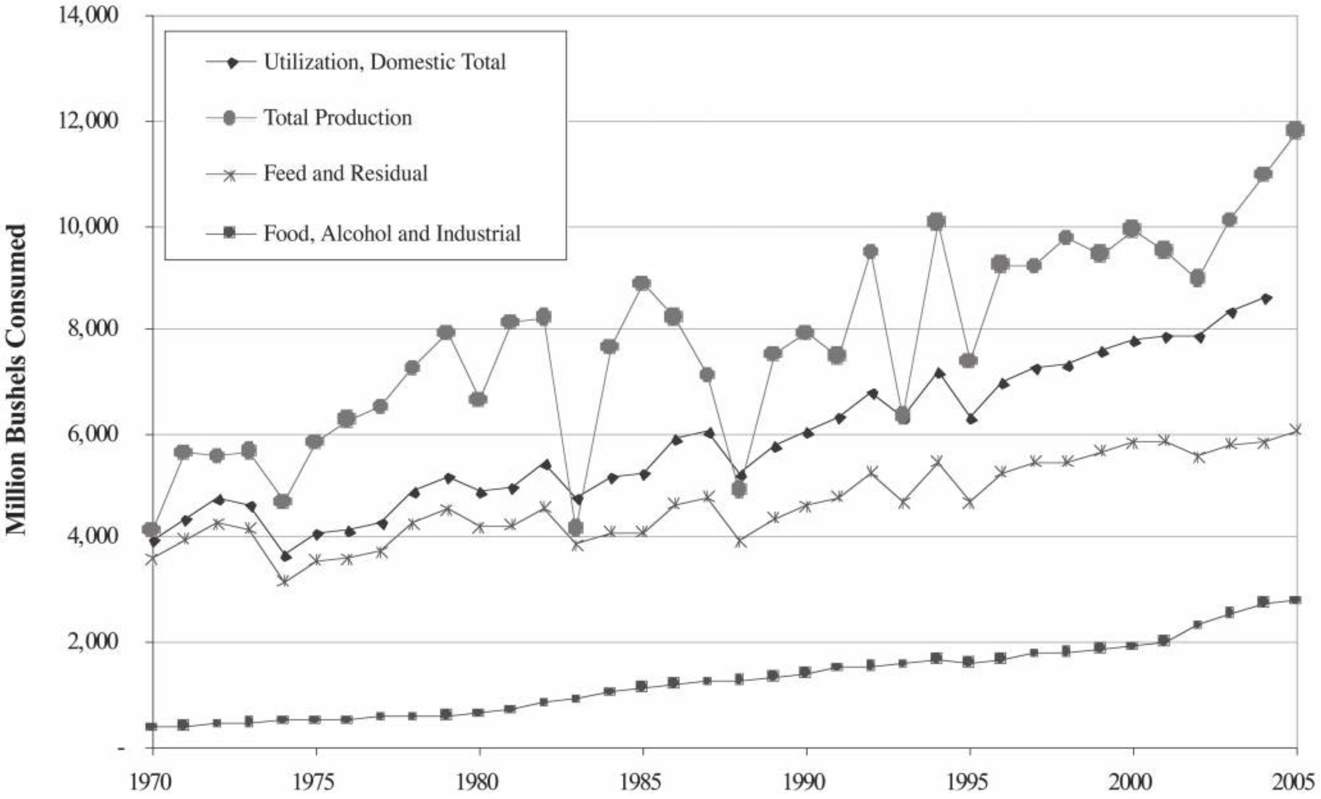


Fig. 1. Production and utilization of corn in the United States *(2)*.

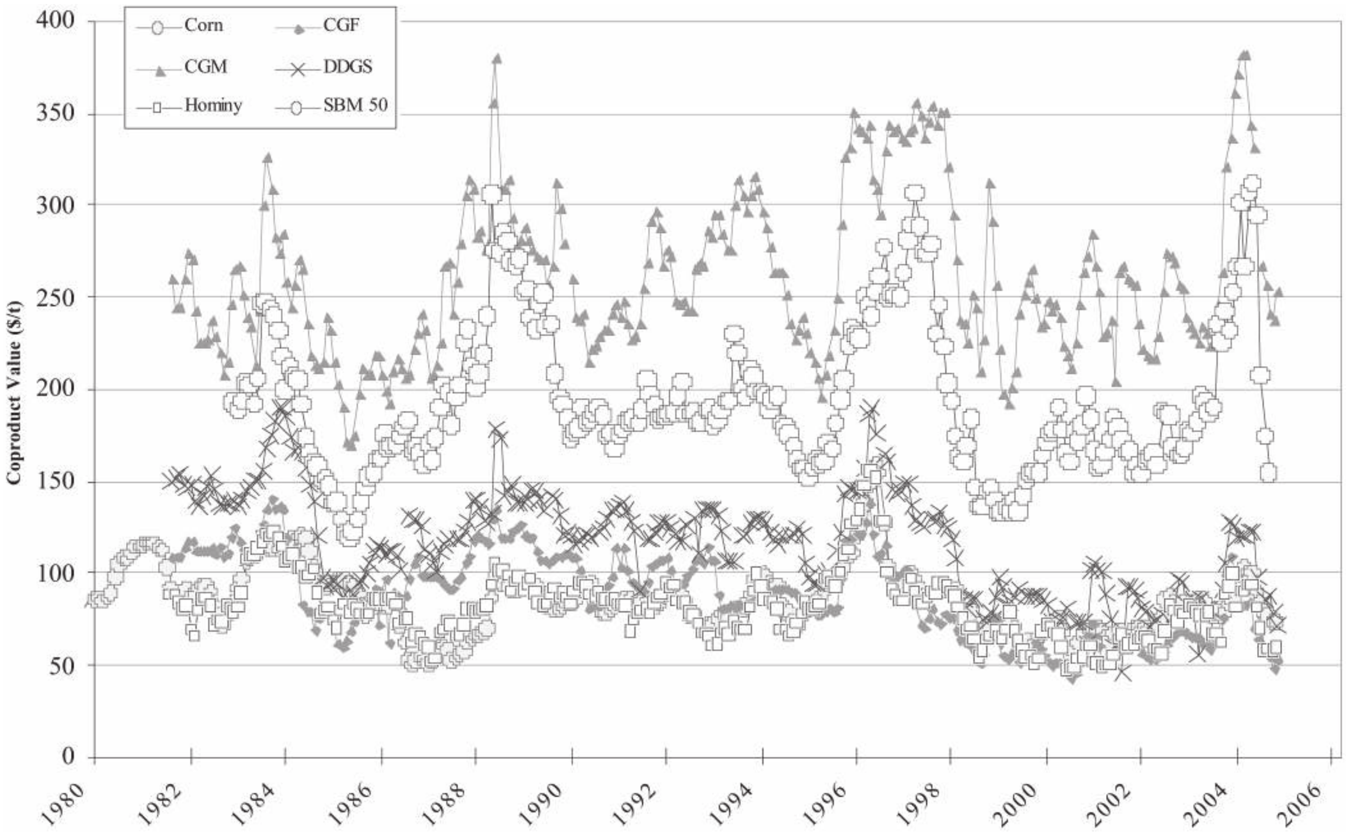


Fig. 2. Price of coproducts from corn processing *(2)*.

processing, only one coproduct (DDGS) is 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.

Several impediments must 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 the 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 phosphorous concentrations of coproducts will pose important waste disposal challenges for many ruminant producers. Reducing the phosphorous content could reduce these concerns and prevent potential adverse effects on ruminant markets. Variability in the 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. In this article, we review technologies used to convert corn into ethanol, compare characteristics and marketing limitations of coproducts, examine market issues, and 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 with 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. Coproducts made by each process also compete in the market, causing relative coproduct values to be interdependent. 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, are 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 United States.

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, such as glucose, high fructose corn syrup, ethanol, and other chemicals. In wet milling, corn is fractionated into four components (i.e., starch, germ, fiber, and protein). Five basic processing steps are used to achieve separation: steeping, germ recovery, fiber recovery, protein recovery, and starch washing (Fig. 3).

In the first step, corn is steeped in a solution of weak sulfurous acid (2000 ppm S as SO_2) for 24–48 h 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 (4–8% solids) is the material remaining after the steeping operation; heavy steepwater (35–40% solids) is the material following concentration of light steepwater by evaporation. Steepwater solids contain 45–50% total protein (dry basis [db], as $N \times 6.25$; Table 1); much of the protein (N) in the steepwater can be in the form of amino acids *(13)*. Steepwater solids contain water-soluble proteins originating from the germ and proteins from other corn components that 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 *(14)*. Owing to high energy costs associated with evaporation and high osmolarity, heavy steepwater is not concentrated to >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's components, because steeping increases the fat concentration *(15)*. 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 22–24% 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 >99.5% (db) (Fig. 3).

Gluten protein is concentrated using a 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 approx 5% of initial corn solids. CGM has high protein (65–67% db) and low fiber content; it is used primarily in nonruminant and companion animal diets.

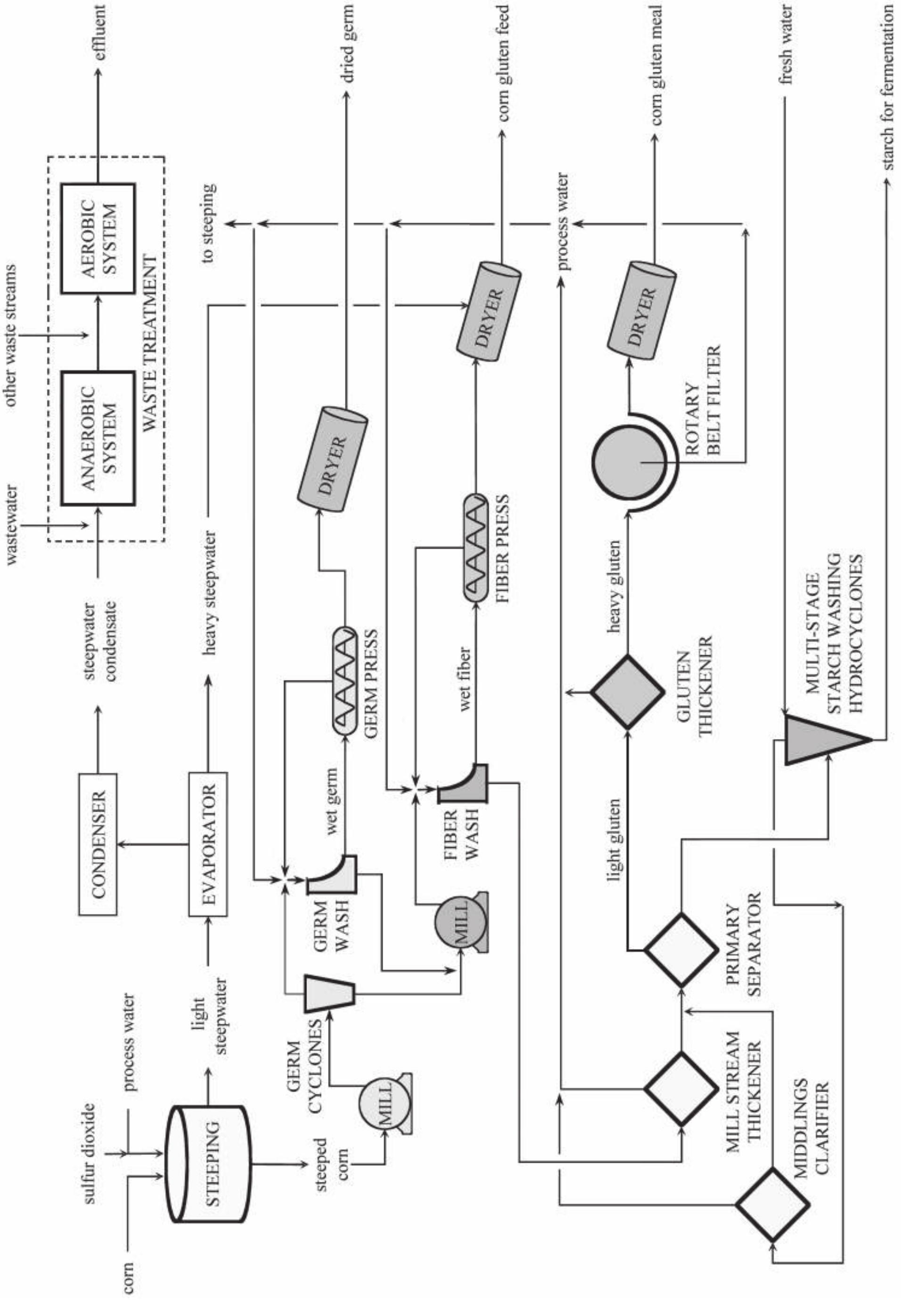


Fig. 3. Corn wet-milling process.

Table 1
Composition of Main Processing Streams and Coproducts From Ethanol Processes

Process	Coproduct	Solids (g/100 g)[a]	Protein[b] (g/100 g db)	Crude fiber (g/100 g db)	Neutral detergent (g/100 g db)	Fat (g/100 g db)	Ash (g/100 g db)	NFE[c] (g/100 g db)
Wet milling[d]	Light steepwater	10.5	46	—	—	—	16	38
	Fiber	—	9	10	0	6	2	73
	CGF[e]	90.0	23.8	8.9	35.5	3.5	6.8	55.7
	Germ meal	90.0	26	—	4	2	5	56
	Light gluten	4.5	69	1	—	2	2	26
	CGM[f]	90.0	65	1.3	11.1	2.5	3.3	25
	Distillers solubles[g]	44.1	22.4	—	—	12.1	11.1	—
Dry grind	Beer[h]	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[i]	84.3	29.6	4.2	—	9	—	—
Dry milling	Hominy feed[j]	86.5	11.9	6.7	4.2	2.7	0.65	
	Flaking grits[k]	86.2	8.7	0.3	—	0.5	0.2	90.3
	Brewer's grits[k]	88.3	8.7	0.5	—	0.8	0.3	91.9
	Cornmeal[k]	88.0	8.0	0.6	—	0.8	0.5	92.1
	Corn cones[k]	88.5	9.0	0.5	—	0.7	0.3	91.9
	Flour[k]	88.0	6.8	0.7	—	2.5	0.7	91.5
	Germ[j]	90.4	17.5	6.3	—	26.3	7.4	38.4
	Bran[j]	90.0	3.8	17.2	—	1.0	1.0	—

[a] Solids data for dry grind (beer, wet grains, syrup, DDGS) (Rausch et al. *[6]*); light steepwater and light gluten from Rausch et al. *(7)*.
[b] $N \times 6.25$.
[c] Nitrogen-free extract.
[d] Loy and Wright *(8)*.
[e] Corn gluten feed.
[f] Corn gluten meal.
[g] Belyea et al. *(11)*.
[h] Rausch et al. *(6)*.
[i] Maisch *(12)*.
[j] Duensing et al. *(9)*; NFE column determined as "starch by difference."
[k] Alexander *(10)*.

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, fat, and ash content (Table 1). Residual solids after fermentation are mixed with CGF and used as animal food ingredients. CO_2 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, the 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 the latter, has only one major coproduct to market besides ethanol (Fig. 4). A dry-grind facility processing 1000 metric t/d and producing 150 million L/yr of ethanol will cost $50 million to construct in the United States. Basic steps in the dry-grind corn process are grinding, cooking, liquefaction, SSF distillation of ethanol, and removal of water from stillage to form DDGS (Fig. 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 corrugated rolls rotating at different speeds exert compressive and shearing forces to decrease particle size.

The ground corn is mixed with water, resulting in a slurry that 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 CO_2 and transferred to a holding tank called a beer well. 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 *(16)*.

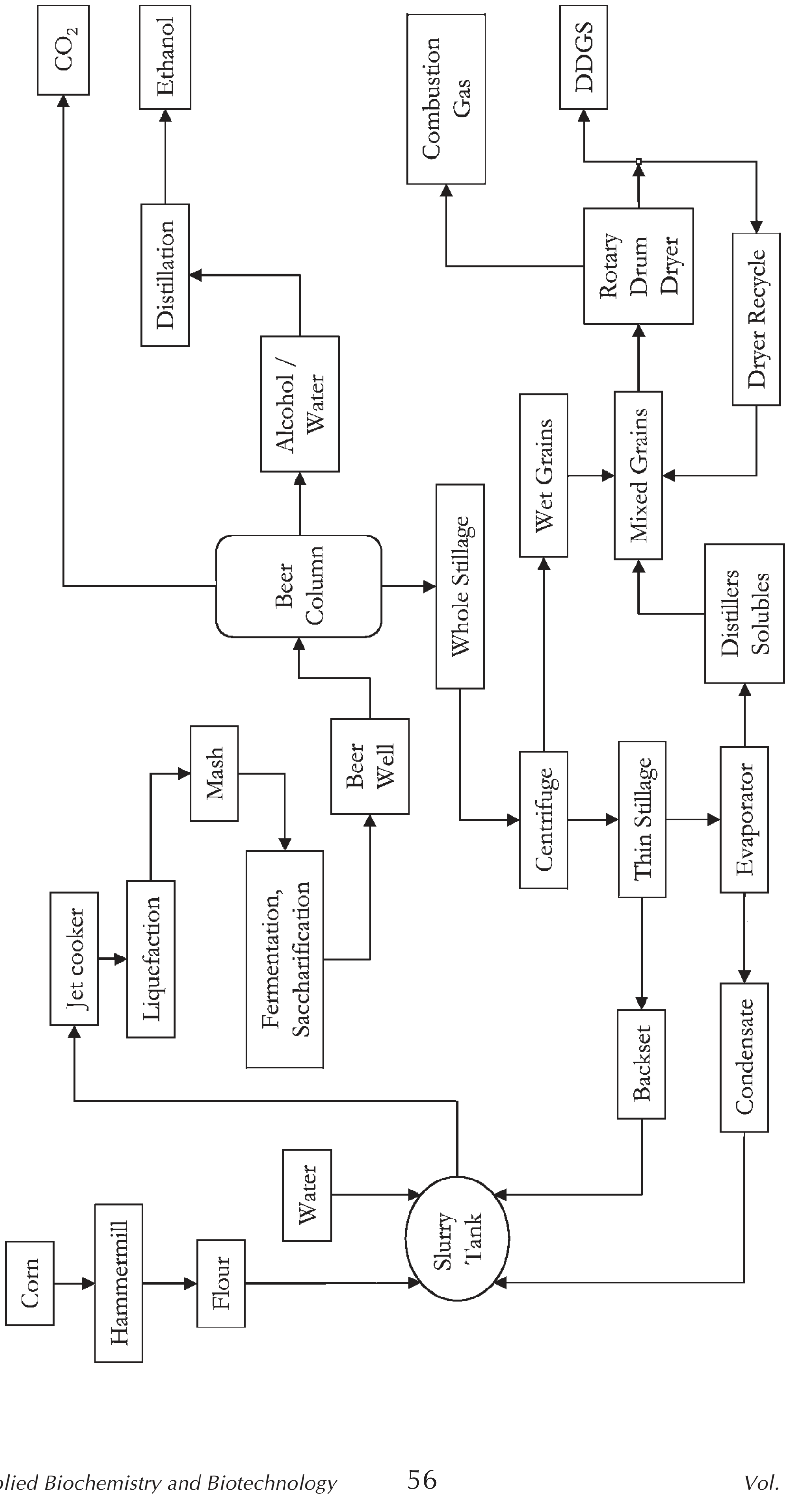


Fig. 4. Dry-grind corn process.

Whole stillage is withdrawn from the bottom of the distillation unit and is centrifuged to produce wet grains and thin stillage (Fig. 4). Using an evaporator, thin stillage is concentrated to form condensed DS (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 CO_2. 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 CO_2 produced from fermentation.

Dry Milling

Corn dry milling is primarily a physical separation process of corn components in which germ (fat), tip cap and pericarp are 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% (Fig. 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 complete as in wet milling; small amounts of pericarp and endosperm remain attached to the germ and, therefore, decrease the oil concentration of the germ fraction. Overall, the coproducts from the 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 (35–40% 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 brewer's 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).

Summary

Corn wet milling and dry-grind processing account for nearly all ethanol production, whereas dry milling accounts for very little. The three processes (wet milling, dry grind, and dry milling) use different equipment and processing conditions, which result in coproducts that have

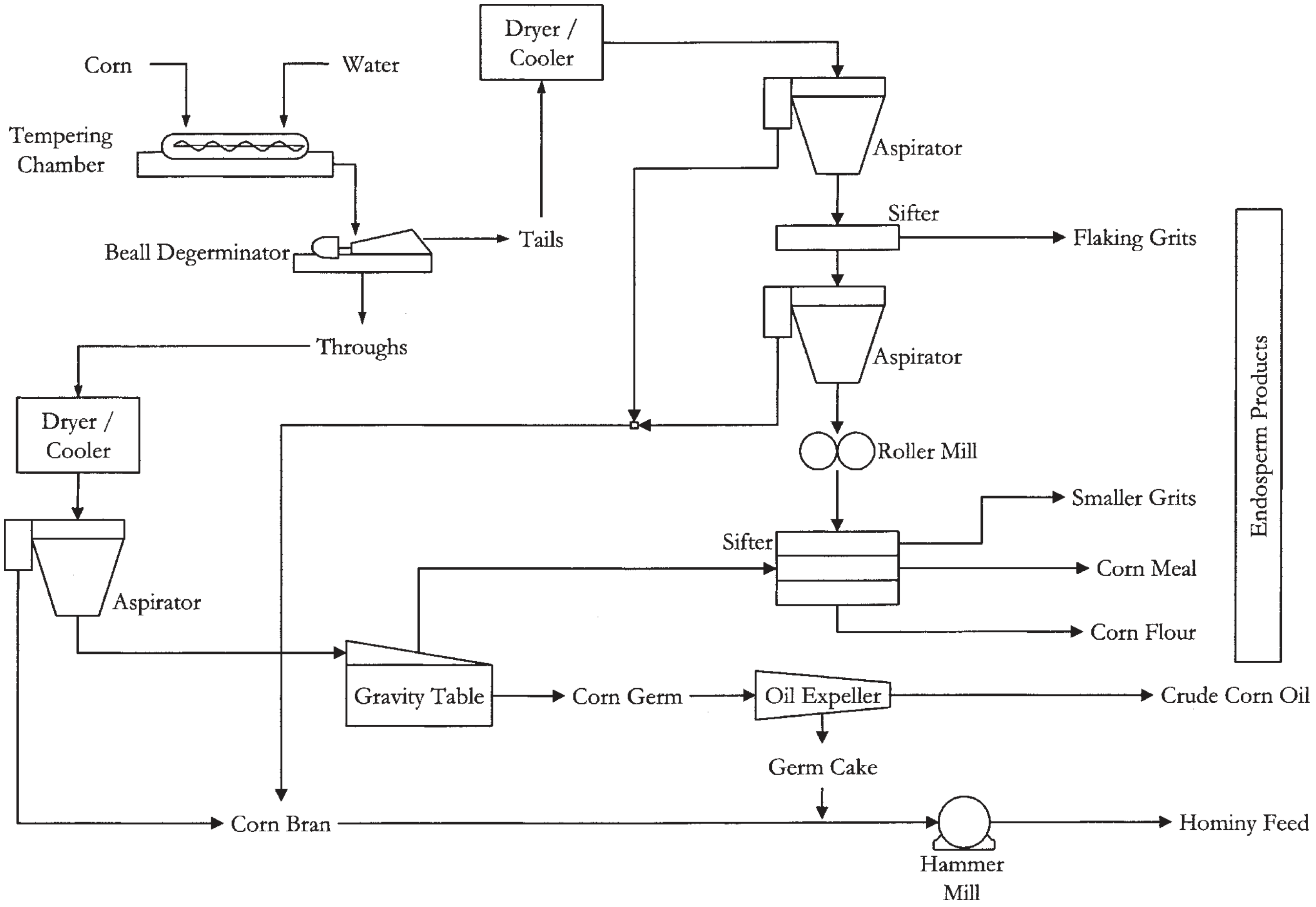


Fig. 5. Corn dry-milling process.

Table 2
Summary of Ethanol Processes, Primary Products, and Coproducts

Process	Brief description	Primary products	Coproducts
Wet milling	Corn is steeped and lightly ground, germ is removed and finely ground, fiber is removed, protein is separated from starch, and starch is further processed. This results in a 99.5% pure starch product.	Starch, ethanol, high fructose corn syrup	Corn oil, CGF, CGM, CO_2
Dry grind	Corn is ground, cooked, liquefied, saccharified, fermented, and distilled for manufacture of ethanol.	Ethanol	DDGS, CO_2
Modified dry grind	Corn is soaked and lightly ground; germ and fiber are removed and finely ground, cooked, liquefied, saccharified, fermented, and distilled for manufacture of ethanol.	Ethanol	DDGS, germ (corn oil), fiber (nutraceuticals), CO_2
Dry milling	A small amount of water is added to corn, and the kernel is abraded to separate the components of pericarp, germ, and endosperm. The remaining process is primarily physical size separation.	Flaking grits	Brewer's grits, small grits, cornmeal and corn cones, corn flour

different analytic 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 for converting corn into ethanol and other useful products (wet milling, dry grind, and dry milling) 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 food industries. Because of its protein content, the market value of CGM often is greater than $330/metric t (Fig. 2), making it a high-value coproduct. CGM has relatively high phosphorous 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 phosphorous requirements; therefore, high phosphorous concentrations in CGM are an advantage. However, high phosphorous 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 *(19)*. When CGM is added to typical nonruminant production diets, the sulfur concentration of the resulting diet will be below this range and would not be expected to have adverse effects. 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 *(19)*. 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

Table 3
Comparison of Typical Coproduct Yields and Historic Values for Ethanol Processes

	Typical coproduct yields		Value	
Process	(per bu corn)	(per metric t corn)	($/metric t)[a]	($/t)
Wet milling[b]	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[e]	286 kg	115.10	104.64
Modified dry grind[c]	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[d]	Flaking grits	120 kg		
	Brewer's grits	380 kg	264	240
	Cornmeal	60 kg	346	314
	Hominy feed	350 kg	86	79
Corn			92	84
SBM 44			198	180
SBM 50			210	191

[a] ERS *(2)*; based on data available from 1994 to 2004.
[b] Wet milling yields from Johnson and May *(15)*.
[c] Modified dry-grind yields from Singh et al. *(17)*.
[d] Yield ranges from 15 to 17 lb/bu.
[e] Dry-milling yields from Brekke *(18)*.

Table 4
Nutrient Profiles of Ethanol Coproducts and Corn *(19)*

Item (g/100 g)	Corn	CGM	CGF	Germ meal (db)	DDGS	Hominy feed	Syrup[a]	Wet grains[a]
Protein	10.9	67.2	25.6	22.3	25.0	11.5	19.7	33.4
Ether extract	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	—	—
Cell-wall	9.0	14.0	—	—	44.0	55.0	—	—
Lignocellulose	3.0	5.0	—	—	18.0	13.0	—	—
Crude 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		

[a] Unpublished data.

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 *(20)*. Because of these concentrations, CGM often is added to poultry diets to improve pigmentation of poultry products. A view commonly held by personnel in the animal food industry is the composition of CGM can vary substantially from batch to batch. However, there are few published data to document the extent of variation *(7)*.

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 with the soluble fraction in corn and DDGS (34 and 33 g/100 g db, respectively) *(21)*. 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 phosphorous content (0.82 g P/100 g db; Table 4) is a concern. Most ruminant production diets contain adequate phosphorous concentrations; adding typical amounts (10%) of CGF will increase the phosphorous content of the resulting diet. When ruminants consume diets containing elevated concentrations of phosphorus, excretion of phosphorus is increased *(22)*. This can create disposal challenges, because environmental regulations for land application of animal wastes are based partly on phosphorous concentration and are becoming more restrictive. Animal producers who have access to cropland with soils having high phosphorous concentrations and/or who have limited cropland for waste disposal must minimize use of high-phosphorous dietary ingredients, such as CGF *(23–27)*.

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 is small in particle size; it has little effective fiber and does not invoke much, if any, rumination (chewing) behavior *(28)*. 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 *(29)*. However, because of the 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 *(29)*. 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 a 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 *(30)*. 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 a highly desirable ingredient for nonruminant diets because of essential amino acid concentrations (Table 4). It also is commonly used in companion animal diet formulations. There are limited contemporary published data on the characteristics of corn germ meal and on the performance of animals consuming diets containing this coproduct *(20)*.

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 its high protein and fat (energy) contents, DDGS is used widely as a dietary ingredient for ruminants with large demand for nutrients (e.g., 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 *(21)*. Consequently, DDGS often are 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, the high phosphorous content of DDGS (0.71 g P/100 g db; Table 4) is a concern, because it increases the phosphorous 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. *(31)* reported that 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 0.33–0.68 g S/100 g db. We *(32)* have limited data that corroborate the data of Shurson et al. *(31)*. 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 thiamine available to be absorbed from the rumen and results in an effective thiamine deficiency. Thiamine deficiency causes brain lesions (polyoencephalamalacia). The bacteria also produce an analog that inhibits certain enzymes involved in energy metabolism *(33)*.

DDGS is palatable most to animals; ruminants readily consume diets containing DDGS *(34)*. The high fat content of DDGS (10.3 g/100 g db) can impose intake limits under certain conditions. DDGS are not pelleted, but the meal form is easy to handle in mechanical systems. Although some of the DDGS is sold in wet form, most is dried prior to marketing. DDGS in wet form is prone to deterioration, especially in warmer weather; consequently, the use of wet DDGS is limited to producers located close to dry-grind plants.

There is considerable discussion regarding DDGS color 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, one dry-grind facility obtained a set of samples of dark DDGS as well as normal-colored samples. We analyzed these samples for bound protein content (as pepsin N). We found that the bound protein was increased in some samples but not all. Powers et al. *(35)* 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 DDGS color; however, Powers et al. *(35)* estimated that dark-colored DDGS had 21% of the total protein in the bound fraction, compared with 13% for the normal DDGS (a 61% increase in bound protein content).

Syrup (Condensed DS)

Although DDGS is the main coproduct that dry-grind plants market, they occasionally market syrup. Because syrup is difficult to dry to a free-flowing powder, it is handled in liquid form and added directly as a dietary ingredient. Because of high water content, its use is limited to local producers. Syrup typically contains 30–40 g dry matter/100 g; the 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 P are high; the presence of elements in such high concentrations raises questions about long-term physiologic 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 the nutritional profiles of wet grains. Wet grains were characterized by NRC *(19)* as containing 43% neutral detergent fiber, 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 it is representative of modern dry-grind processing. Limited data from our laboratory suggest that wet grains from dry-grind processing have lower fiber and higher protein (30%) and higher fat (13%) than the wet grains reported by the NRC *(19)*. Mineral concentrations of wet grains appear to be low (e.g., 0.11% Ca, 0.43% P, 0.18% K) *(19)*.

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 and, 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 fat content, it has an energy value similar to that of corn. Hominy is used in ruminant diets and is palatable despite its small particle size. Its rate of digestion is higher than that of 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 both the ethanol processor and the end user (animal producer). Because ethanol is a primary product, plant managers often devote most of their time and resources to managing 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 a lack of basic information needed to address certain problems. For example, the composition of DDGS can have large fluctuations. Causes of the variation are not well documented; this impairs the 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 reduced; 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 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 economic 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 maximum productivity. Selecting the most economic ingredients can be complicated because of differences in the 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 with conventional ingredients *(36)*. 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 (e.g., 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. Table 5 illustrates 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/metric t, respectively, the break-even price for DDGS is \$166/tonne (Table 5). When the prices for corn and soybean meal increase to \$118 and \$300/metric t, respectively, the break-even price for DDGS increases to \$219/metric t. These data (Table 5) are illustrative of several points: First, break-even price changes with change in either corn (energy source) or soybean meal (protein source). Second, changes in soybean meal price affect break-even prices more than corn (because protein is priced higher than energy). Third, market prices of CGF and DDGS (Fig. 2) rarely exceed break-even prices. Finally, 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 maximum 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. Reducing the amount of starch fed to ruminants can reduce the potential for acidosis; acidosis can reduce digestibility of the diet and lead to long-term health issues. Another common example is adding DDGS to reduce the degradability of protein in diets, due to high energy and protein

Table 5
Equivalent Nutrient Value of Ethanol Coproducts for Various Corn and Soybean Meal Prices *(37)*

Corn		SBM[a]		DDGS		CGF		CGM	
($/bu)	($/metric t)	($/t)	($/metric t)	($/t)	($/metric t)	($/t)	($/metric t)	($/t)	($/metric t)
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

[a] Soybean meal (50% crude 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 (Fig. 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 this amount increases, the supply of coproducts necessarily will increase, which will continue to put downward pressure on the market value of coproducts. This appears to be the case with DDGS, which has decreased relative to the value of corn since the 1990s (Fig. 2). The situation is complicated further by the supply and market value of corn, soybeans, and other commodities that have direct and/or indirect effects on the market value of the coproducts. Thus, maintaining a viable, sustained market, while important to the 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 (approx 1 wk or less). 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 oversupply 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- and long-term effects on the market price of ethanol coproducts.

Variability

The chemical composition of many coproducts can vary markedly; this has been documented *(31,38–40)*. Most nutrients are affected, but protein probably is the most important because of economic and biologic implications. The 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% (unpublished data; *[40]*). DDGS typically is marketed with a conservative estimate of protein content (i.e., 25%) so that label specifications are attained. However, because of variation, the protein content of a given batch of DDGS could actually be 5–10% 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 0.5–1.0 lb 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 physiologic effects. From a marketing standpoint, it also means that about one-fourth of DDGS protein is undervalued 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 *(39)*. Clevenger et al. *(32)* measured the concentrations of elements of DDGS from different dry-grind plants; for many elements, the variation among plants was >50%. Others *(31,38)* 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 *(31,32,38–40)* have shown the contemporary analytic data for many coproducts differ substantially from published sources, such as NRC *(19)*. A clear explanation for the discrepancies between contemporary data and historic 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.

There could be several reasons for the variability in the composition of DDGS from dry-grind plants. DDGS is produced by the blending of two parent streams: wet grains and syrup (Fig. 4). We have shown that the composition of either stream can vary considerably; for example, the protein content of syrup can vary from 16 to 30% *(6,41)*. The protein content of wet grains, although considerably higher than of syrup, also can vary. In addition to variation in the 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 largely. In addition to these two sources of variation, processors sometimes market either wet grains or syrup separately, changing 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 biologic events in the fermentors. 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 more practical. When DDGS is placed in storage, they are carried from the dryers to the storage facility by conveyer. Batches of DDGS 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, the composition of DDGS can vary substantially within a shipping unit (truck or railcar), and this makes diet formulation difficult.

Phosphorous Content

Eutrophication is the process in which bodies of water naturally age; it is caused by the presence of nutrients and is characterized by the growth of algae and reduced oxygen levels. Bodies of water are classified as eutrophic if the phosphorous concentration is 31 μg P/L or higher *(42)*. High phosphorous 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 phosphorous concentration of bodies of water. Reducing phosphorus in animal wastes and controlling the application of animal wastes to land are needed to reduce pollution of surface waters. Many bodies of water in the United States are experiencing increasing phosphorous content; recreational lakes in southwest Missouri are examples. Phosphorous concentrations of these lakes have been increasing for the past several decades, and 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 phosphorous content of diets is one aspect of reducing the phosphorus in animal wastes. The phosphorous 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 the requirements of most ruminants (Table 4).

High phosphorus in diets can increase phosphorus in animal wastes *(22)*. Regulations for disposal of animal wastes are becoming increasingly stringent and are based, at least partially, on phosphorous content. Most ruminant diets have adequate or nearly adequate phosphorous concentrations. Adding high phosphorous ingredients to typical ruminant diets will increase unnecessarily dietary phosphorous concentrations and phosphorous content of wastes *(23–27)*. High phosphorous wastes may cause disposal difficulties for some producers because land application of animal wastes is based primarily on phosphorous 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 a 25 kg/d diet that contains 3 mg P/kg of diet will consume 75 g P/d. About 75% (56 g P) of the phosphorus will be recovered in animal wastes. This amounts to 4124 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 (2.2–22 kg P/ha) for crop growth than grain crops, such as corn (28 kg P/ha or more) *(43)*. This affects the amount of animal waste that can be land applied. Adding DDGS to the diet could increase the phosphorous concentration to 4 mg/kg. This would increase phosphorus excretion to about 5600 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. It is clear that 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, approx 20 million hogs were marketed in 2004; approx 45 million each of broilers and turkeys were marketed in 2003 *(44)*. If half these market animals were fed diets containing 10% of a modified (low-fiber, high-protein) DDGS, they would consume about 3000 t/d, or the output equivalent of about 10 typical dry-grind ethanol plants.

The high phosphorous concentration of conventional DDGS poses a potential market limitation for ruminants, because of implications on animal waste disposal. Technologies that reduce the phosphorous 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 larger amounts of DDGS to ruminant production diets would not increase dietary phosphorus significantly and would 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 *(6,41)*. 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 would remove water, solving two processing issues.

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, increasing use in a large market segment.

An Additional Processing Challenge: Water Removal

Need for Water Removal

Coproduct streams from corn processes are large in volume, are relatively low in total solids (<20%), and contain valuable nutrients. Although 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 wet ingredients and shipping costs, the sale of wet ingredients is limited to a relatively small area surrounding a plant. Extending the marketing area for wet material increases the risk of microbial growth, leading to putrefaction and risk of mycotoxin production.

Removal of water from corn-processing streams is costly in terms of energy and involves the use of equipment that contributes 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 48–72 h. CGF, CGM, and DDGS are marketed on an 88–90% solids basis. Light steepwater, light gluten, and thin stillage streams have 7–11, 4–6, and 5–10% 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. The 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 centrifuging, followed by drying or evaporating. 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, because 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 (4–6% solids) is concentrated to form heavy gluten (10–14% 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 DS) is produced from concentrating thin stillage (5–10% solids) by evaporation to 35% solids. DDGS is formed by mixing syrup with wet grains and drying to 90% solids (Fig. 4).

Membrane filtration is a new method used for the removal of water in corn-processing streams. Membranes can improve process efficiency; membrane separations can result in water suitable for recycling within the processing facility *(14,45,47)*. 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 (e.g., dairy) but are not used widely in the corn-processing industry *(14)*.

The 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 1.2–23 kJ/kg water removed from the coproduct stream. By contrast, drying requires inputs of 700–3700 kJ/kg water removed from the coproduct, an increase in energy input of two orders of magnitude (Table 6). As a general rule, the initial 90% of water to be removed by dewatering requires approx 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 nonruminant diets. Due to the importance of optimal and consistent growth rates, the nonruminant production industries have a lower tolerance for variation in composition than the ruminant animal industry. With uncertain energy costs, water removal will have an increasing economic importance 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 its primary products and coproducts is presented in Table 2. The data in Table 2 as well as the preceding discussion make it clear that, compared with 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 (750–805 L/metric t of corn). However, quantities and values of coproducts can vary. The dry-grind process yields 286 kg/tonne of DDGS (worth \$115.10/metric t, based on ERS data from 1994 to 2004 *[2]*) or a total income of \$30.85/metric t of 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 the ethanol-processing industries; lack of a diversity of marketable and valuable coproducts makes 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 to be described later, have been proven at experimental scale; these provide opportunities to improve coproduct marketability.

Modifications to the Dry-Grind Process

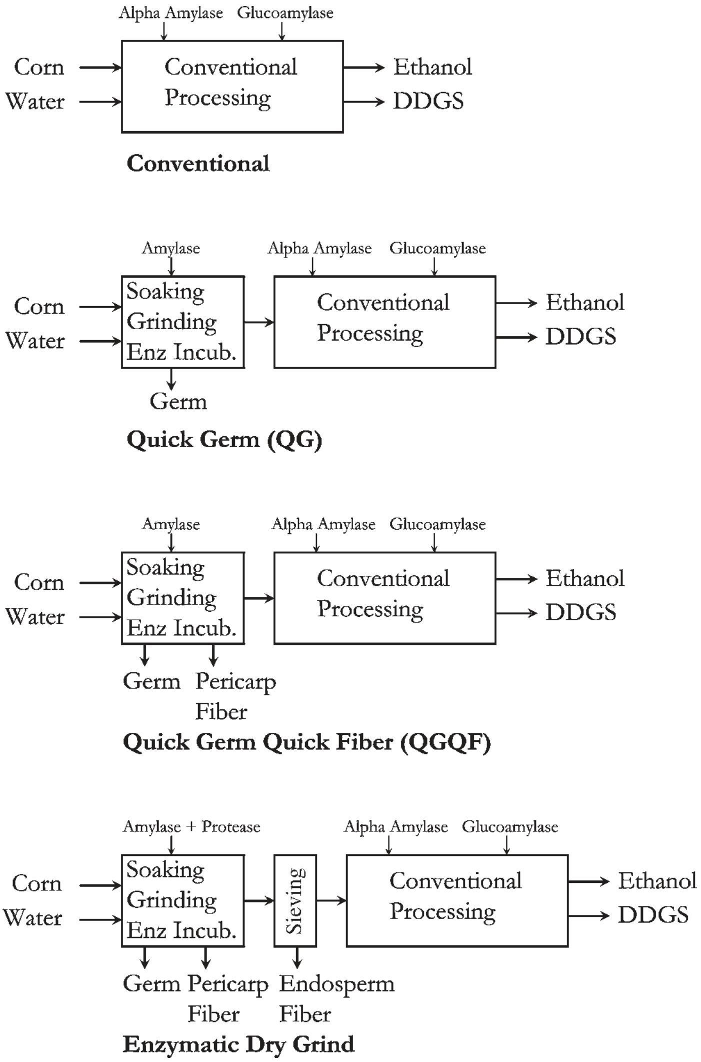
New processes have been developed to address the issue of coproduct value. In modified dry-grind corn processes called quick germ (QG), quick germ quick fiber (QGQF), and enzymatic dry grind, whole corn is soaked in water and lightly ground in a conventional disk attrition mill (Fig. 6) *(17)*. Enzymes 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.

Table 6
Energy Requirements to Remove Water From Coproducts

	Energy input		Reference
	(BTU/lb_{H_2O})	(kJ/kg_{H_2O})	
Theoretical	972	2260	
Filtration, membrane			
Microfiltration	3	7	Wittwer, S., personal communication, September 17, 2004
Ultrafiltration	4	9	Wittwer, S., personal communication, September 17, 2004
Reverse osmosis	47	110	*45*
Filtration, vacuum belt	10	23	Merediz, T., personal communication, September 22, 2004
Pressing			
Germ press	0.5	1.2	Wideman, J., personal communication, March 3, 2005
Fiber press	3	7	Wideman, J., personal communication, March 3, 2005
Centrifugation			
Gluten thickener centrifuge	2–3	4–7	Merediz, T., personal communication, September 22, 2004
Stillage (decanter) centrifuge	2–3	4–7	
Evaporation			
Single effect	1160	2700	*45*
Triple effect	559	1300	*45*
Mechanical vapor recompression	300	700	*45*
Drying			
Dryer	1720	4000	*45*
Direct heated pneumatic dryer (ring, rotary, fluid bed), partial gas recycle	1150–1400	2675–3257	Crankshaw, C., personal communication, September 1, 2004
Indirect rotary steam tube dryer, not including steam generation efficiency	1350–1500	3141–3490	Crankshaw, C., personal communication, September 1, 2004
Indirect heat pneumatic dryer with recuperative heat exchanger	1100–1150	2559–2675	Crankshaw, C., personal communication, September 1, 2004

Indirect rotary steam tube dryer for germ	1400	3257	Crankshaw, C., personal communication, September 1, 2004
Fluidized-bed dryer for corn germ	1522	3541	McAloon, A., personal communication, August 31, 2004
Fluid-bed dryer for corn germ	1300	3024	Crankshaw, C., personal communication, September 1, 2004
Rotary dryer for corn fiber	1588	3694	McAloon, A., personal communication, August 31, 2004
Rotary dryer for fiber and DDGS	1300	3024	Crankshaw, C., personal communication, September 1, 2004
Rotary drum dryer, direct fired	1350	3140	*16*
Ring dryer for CGF	1571	3655	McAloon, A., personal communication, August 31, 2004
Ring dryer for DDGS	1170	2722	Crankshaw, C., personal communication, September 1, 2004
Ring dryer for gluten and fiber	1250–1300	2908–3024	Crankshaw, C., personal communication, September 1, 2004
Ring dryer for starch, maltodextrin, dextrose, etc. (open cycle)	1600–2000	3722–4653	Crankshaw, C., personal communication, September 1, 2004
Spray dryer	2153	5009	*46*
Spin flash dryer	2047	4762	*46*

McAloon, A., personal communication, August 31, 2004
Crankshaw, C., personal communication, September 1, 2004
Wittwer, S., personal communication, September 17, 2004
Wideman, J., personal communication, March 3, 2005
Merediz, T., personal communication, September 22, 2004



Conventional

Quick Germ (QG)

Quick Germ Quick Fiber (QGQF)

Enzymatic Dry Grind

Fig. 6. Modified dry-grind corn processes *(13)*.

These processes separate germ *(43,49)*, pericarp fiber *(50,51)*, and endosperm fiber *(17)* 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.

QG Process

The QG process involves soaking whole corn in water for 3–12 h before wet processing *(48,49)*. 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 (Fig. 6) for 3 h, which increases the slurry's specific gravity. The adjusted specific gravity allows germ to be recovered by hydrocyclones. The QG process has been shown to be an economic modification to the conventional dry-grind process, requiring $7 million for a 1000 metric t/d (40,000 bu/d) corn-processing facility *(49)*.

Recovery of germ as a coproduct creates options and economic opportunities for the dry-grind corn processor. Based on historic data for 1994–2004, crude corn oil from germ had an average value of $522/metric t compared with $115/metric t for DDGS during the same period *(2)*. 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 fermentor capacity due to removal of nonfermentables from the corn mash and to reduced fouling of the thin stillage evaporators *(49,52–54)*. The QG process is a straightforward process methodology to enhance economic sustainability of ethanol production facilities.

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 mill, and incubated with amylase (Fig. 6). Soaking and incubation parameters are adjusted so that 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 *(51,52)*.

Recovery of pericarp fiber has several advantages compared to the conventional dry-grind corn process. It increases fermentor capacity 6–8%; increased fermentor 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 the potential for including DDGS in nonruminant livestock diets is enhanced *(17)*.

In comparison to other cereal grains, high levels of cholesterol-lowering phytosterol components, i.e., ferulate phytosterol esters, free phytosterol, and phytosterol fatty acyl esters, can be extracted from pericarp fiber *(52)*. 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 *(55)*. These cholesterol-lowering compounds can be used as nutraceuticals and command a high market value.

Owing to germ and fiber removal, nonfermentable solids in the fermentor are reduced, increasing material that can be processed through the fermentor. Savings for using the germ and fiber removal process over the conventional dry-grind corn process were estimated at 1.3¢–1.8¢/L ethanol (5–7¢/gal) *(54)*. The costs of retrofitting a 1000 metric t/d (40,000 bu/d) 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

An additional 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 (Fig. 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 *(56,57)*. Removal of this fiber component, in addition to removal of germ and fiber, increased protein and decreased fiber contents of DDGS from enzymatic dry grind *(17)*.

Additional costs of retrofitting a 40,000 bu/d (1000 metric t/d) 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 *(17)*. Relative to the conventional dry-grind process, the 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/metric t for the conventional dry-grind process to $176, $209, and $238/metric t for QG, QGQF, and enzymatic dry-grind processes, respectively, using methods to estimate nutritional value *(36)*.

Germ fractions recovered from QG, QGQF, and enzymatic dry-grind processes are of a quality that can be used for oil extraction and contain 35–40% 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–$266/metric t (Table 7; *[58]*); no germ is recovered in the conventional dry-grind process.

The method to recover germ from various processes has been shown to change the composition of the germ, especially crude fat (oil) content (Table 8; *[58]*). 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

Table 7
DDGS Composition *(17)* and Coproduct Values
for Conventional, QG, QGQF, and E-Mill Dry-Grind Processes[a]

	Dry grind	QG	QGQF	E-Mill	CGM	SBM
Composition						
Crude protein	28.5*	35.9§	49.3‡	58.5†	66.7	53.9
Crude fat	12.7†	4.8‡	3.9‡	4.5‡	2.8	1.1
Ash	3.6†‡	4.1†	4.1†	3.2‡	—	—
Acid detergent fiber	10.8†	8.2‡	6.8§	2.0*	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 symbol in a row are not significantly different at a 95% confidence level.

[b] Market value is based on estimates from ref. *58* (*see* Table 8).

[c] Break-even prices are based on historic market values (1994–2004) of corn ($83.92/t or $92.31/metric t) and 50% soybean meal (SBM) ($191.16/t or $210.28/metric t) and calculations from refs. *36,37*.

facilities is large. A germ coproduct that does not contain high oil concentrations (i.e., 35–40% db oil) will not be accepted at large extraction facilities, reducing the market value of the lower-purity coproduct. In the wet-milling process, recovered germ will have a value of $218–$247/metric t. In dry milling, recovered germ will be worth $128–$150/metric t, which is similar to the value of DDGS in the conventional dry-grind process ($115/metric t). 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. Overall capital costs are higher for modified dry-grind processes (e.g., $0.38, $0.40, and $0.42/L annual ethanol capacity for QG, QGQF, and enzymatic dry grind, respectively) compared with conventional dry grind (e.g., $0.33/L annual ethanol capacity). These estimates are only for capital investment and do not reflect the increased revenue from higher coproduct values for modified dry-grind processes; they are less than the capital investment required for corn wet milling ($0.62–$0.92/L annual ethanol capacity) *(15)*. Lower capital investment allows smaller processing facilities to be built and operated economically in regions where corn supply is readily available.

Table 8

Composition, Yield, and Value of Germ Derived From Laboratory and Commercial Corn Processes *(58)*

Milling process	Oil (% w/w)	Protein (% w/w)	Starch (% w/w)	Ash (% w/w)	Yield (% corn dry wt)	Germ value ($/lb germ)	Germ value ($/metric t)
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-h SO_2 steep)	38.8	18.4	11.6	2.3	7.5	0.113	249
QG (12-h 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		

Membrane Filtration for Water Removal and Improved Coproduct

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 using 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 evaluated the effectiveness of membrane filtration in modern fuel ethanol plants. Some have studied removal of water and reduction of wastewater strength *(59–62)*, 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 *(63,64)*. We showed the potential of microfiltration to remove considerable amounts of water (and elements as well). Templin et al. *(63)* 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 sixfold in simple batch filtration experiments. In larger-scale membrane filtration work *(64)*, light gluten separation achieved a nearly fivefold increase in total solids in membrane concentrate while permeate concentrations of total ash were five times higher than in the original light gluten stream. The ability to remove ash (and, presumably, phosphorus) from coproduct streams as well as the requirement of small amounts of energy for dewatering (Table 6) illustrate the potential for broader use of this technology in corn processes.

High phosphorous content in corn-processing coproducts represents an important environmental issue, as discussed earlier. One of the challenges to affecting reduced phosphorous content is a lack of understanding of the flow of phosphorus in corn processes. Many corn processors are unaware of the phosphorous concentrations in various streams of their process and, therefore, are unable to identify opportunities for changing phosphorous content in final coproducts. Several processors have indicated that 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 the 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 *(6,65)*. We used a laboratory-scale microfiltration system to treat steepwater and gluten streams from a wet-milling plant. This system effectively reduced the ash content of both light steepwater and light gluten (data not shown);

more work is needed to determine the removal of phosphorus by the use of membrane filtration.

Conclusion

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, owing 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 that they can be handled and stored safely and efficiently and increased awareness of the consequences of high phosphorous 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 the economic feasibility of ethanol production in rural communities. With rapid changes in the ethanol industry expected in the next 5–10 yr, additional work is needed to develop proactively ethanol production methodologies that mutually meet economic, nutritional, and environmental concerns.

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