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Corn Processing Coproducts from Ethanol Production

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Introduction

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 tend to be larger, generating significant volumes of ethanol. 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 tend to produce smaller volumes of ethanol. Traditionally, most ethanol was produced by wet milling; however, in the past ten years, dry grind capacity has increased rapidly and now accounts for 80% of ethanol production (Renewable Fuels Association, 2007).

Recent growth trends in the dry grind ethanol industry are expected to continue and will increase the volume of DDGS to be marketed. DDGS are desirable to animal producers because of 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; which 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 (Figure 1).

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, 2002, 2003) 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 coproducts. Marketing DDGS is important for dry grind ethanol producers because it is the only coproduct available; their economic sustainability could be strengthened if existing markets could be expanded or new markets could be developed.

There are several impediments to 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 (Rausch and Belyea, 2006). 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. High phosphorus concentrations of coproducts pose important waste disposal challenges for many ruminant producers. 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, thus identifying less costly and more effective approaches for removing water will increase processing efficiency and decrease processing costs.

Technologies (Wang *et al.*, 2005, 2007) 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.

Processes for Converting Corn into Ethanol

Corn is converted into ethanol by two commercial processes: wet milling (Figure 2) and dry grinding (Figure 3). A third process, dry milling, is sometimes confused with dry grinding. Dry milling produces endosperm products such as flaking grits and corn meal as well as the coproducts hominy feed and dry milling germ. It is not used to produce ethanol and, therefore, not a focus of this paper. Each process has unique equipment and technologies that impact the characteristics of the resulting processing streams and coproducts (Table 1). 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

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the process to produce beverage ethanol. However, the beverage ethanol industry is less sensitive to ethanol yield and energy efficiency. Fuel ethanol prices are more directly linked to commodity markets 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. A dry grind facility processing 40,000 bushel (bu)/day and producing 40 million gallons (gal)/year ethanol cost $60 million to construct in the United States. 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. 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 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 affect particle size reduction (Naidu *et al.*, 2007; Rausch *et al.*, 2005a).

The ground corn is mixed with water, resulting in a slurry which is cooked and mixed with amylase, an enzyme. 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 diox-

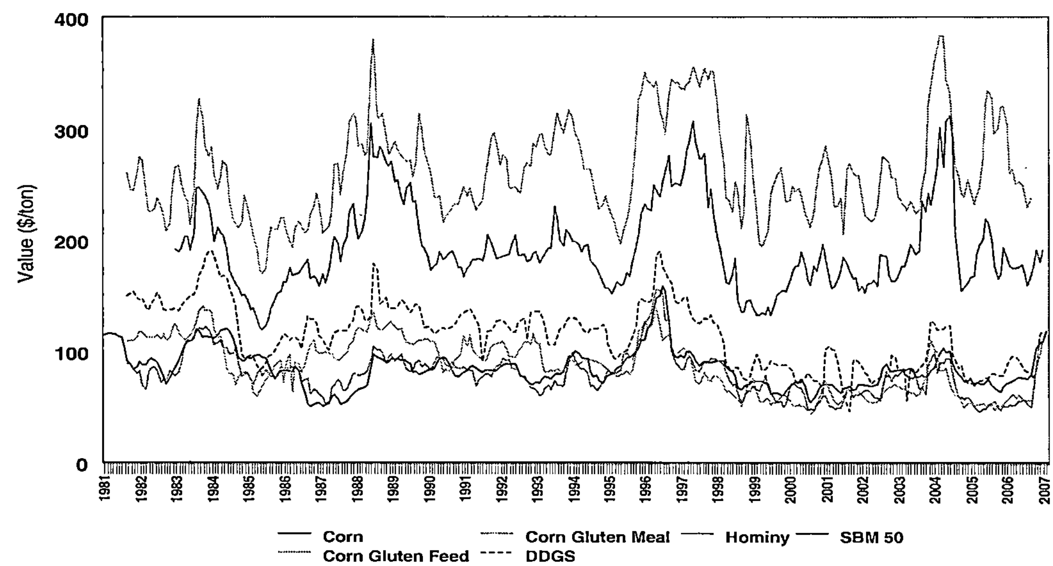

Figure 1: Price of Coproducts from Corn Processing.
Note: SBM 50 = soybean meal, 50% protein.
Source: Economic Research Service (2007).

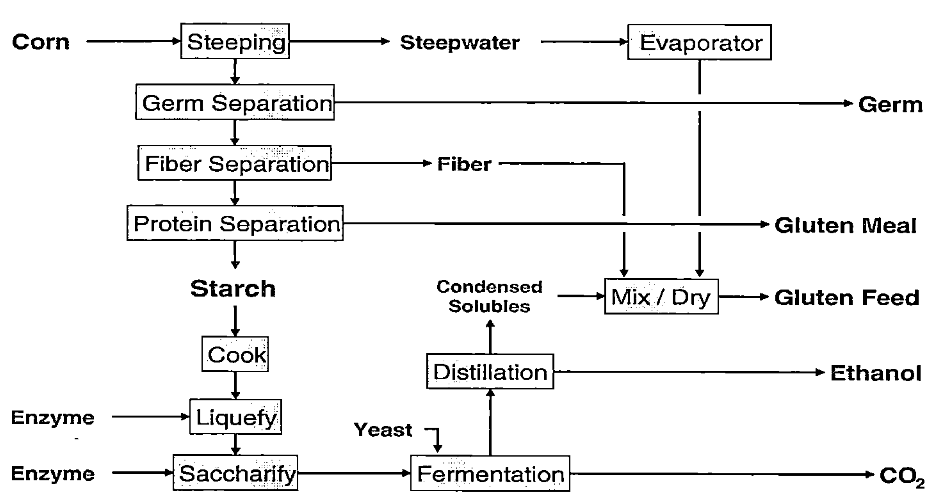

Figure 2: The Corn Wet Milling Process.

Table 1: Composition (g/100 g db) of Main Processing Streams and Coproducts from Ethanol Processes.

Process	Coproduct	Solids (g/100 g)[1]	Protein[2]	Crude Fiber	NDF[3]	Fat	Ash	NFE[4]
Wet milling[5]	Light steepwater	10.5	46	--	--	--	16	38
	Corn gluten feed	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
	Corn gluten meal	10.0	65	1.3	11.1	2.5	3.3	25
	Distillers solubles[6]	4.41	22.4	--	--	12.1	11.1	--
Dry grind	Beer[7]	11.9	29.8	--	--	--	--	--
	Thin stillage	7.1	20.1	--	--	--	--	--
	Wet grains	32.8	33.4	13.8	43.2	7.6	2.2	0.43
	Syrup	27.5	20.1	4.2	22	9.4	7.3	1.12
	DDGS[8]	84.3	31.3	4.2	--	9	--	--
Dry milling	Hominy feed[9]	13.5	11.9	6.7		4.2	2.7	0.65
	Germ[9]	9.6	17.5	6.3		26.3	7.4	38.4
	Bran[9]	10.0	3.8	17.2	--	1.0	1.0	--

Notes: [1] Solids data for dry grind (beer, wet grains, syrup, DDGS), light steepwater and light gluten from Rausch and Belyea (2006).
[2] Nitrogen × 6.25.
[3] Nondetergent fiber.
[4] Nitrogen-free extract (NFE) column determined as "starch by difference"; Duensing et al. (2003).
[5] Loy and Wright (2003).
[6] Belyea et al. (1998).
[7] Rausch and Belyea (2006).
[8] Distillers dried grains with solubles; Maisch (2003).
[9] Alexander (1987).

ide 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. 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. However, the primary market materials for most dry grind processing plants are ethanol and DDGS. Small amounts of wet grains and syrup are marketed. A few processing plants capture and market the carbon dioxide produced from fermentation.

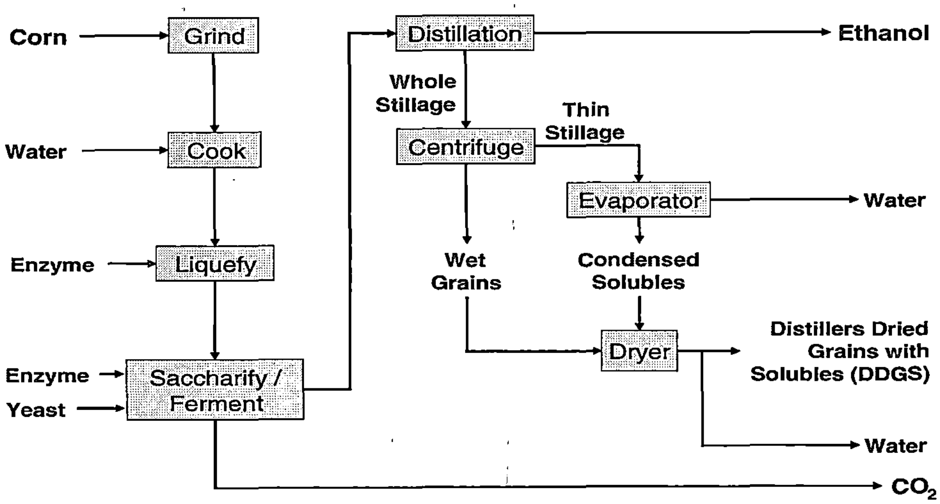

Figure 3: The Dry Grind Process.

Table 2: Coproduct Yields and Values from Ethanol Processes.

Process	Yield, per bu corn	Yield,[1] lb/ton corn	Value,[1] $/ton coproduct	Revenue, $/ton corn
Wet milling[2]	2.50 gal ethanol	89	1.29	115
	4.2 lb germ[3]	150	211	16
	3.0 lb corn gluten meal	107	270	14
	12.4 lb corn gluten feed	443	63	14
			Coproduct subtotal	44
			Total	159
Dry grind	2.75 gal ethanol	98	1.29	126
	16 lb DDGS[4]	571	89	25
			Coproduct subtotal	25
			Total	151
E-Mill[5]	2.54 gal ethanol	91	1.29	117
	3.6 lb germ[3]	129	211	14
	4.6 lb fiber[6]	164	--	--
	7.8 lb DDGS[7]	279	216	30
			Coproduct subtotal	44
			Total	161

Notes: [1] Yields and values for ethanol are in gal/ton and $/gal, respectively; values from Economic Research Service (2007) data for 2001 to 2005 market years except as noted.[3,7]
[2] Wet milling yields from Johnson and May (2003).
[3] 7.5% yield; germ (unextracted) value calculated using method of Johnston et al. (2005). E-Mill germ yield is 85% of wet milling yield. E-Mill germ value assumed equal to WM germ value.
[4] Distillers dried grains with solubles.
[5] Yields from Singh et al. (2005).
[6] Fiber yield increased by 0.6 lb to reflect decrease in germ yield for E-Mill.
[7] Value from Rausch and Belyea (2006) and calculated from Howard and Shaver (1997) and Byproduct Feed Bulletin Board (2003).

Characteristics and Utilization of Coproducts

The two methods for converting corn into ethanol and other useful products use different equipment and processing conditions, resulting in different processing streams and composition. These processes yield coproducts that differ in quantity and economic value (Table 2). Coproducts that result from these streams differ in composition (Table 3). It is important to know the unique nutritional characteristics of each coproduct so that possible strategies can be developed to improve market value for use in animal diets.

DDGS is the only major 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 crude fat, fiber, protein and elements in relatively high (three times the levels in corn) concentrations (Table 3). High fiber content limits 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 grams (g)/100 g dry basis (db)) and a large fraction (67 g/100 g db) slowly degraded in the rumen (Krishnamoorthy *et al.*, 1982). 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 corn gluten feed (CGF). Similar to CGF, high phosphorus content of DDGS (0.71 g P/100 g db; Table 3) is a concern, because it increases the phosphorus content of diets and animal wastes, which can lead to disposal challenges. Based on published data, the sulfur (S) content of DDGS is not high (0.33 g S/100 g db; Table 3). 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). Phosphorus (P) and sulfur can also be issues in coproducts from wet milling, because these elements are concentrated in coproducts (Rausch *et al.*, 2005b, 2007).

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 are 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. DDGS in wet form is prone to deterioration and degrades quickly, especially in

Table 3: Comparison of the Nutrient Profile of Ethanol Coproducts to that of Corn.

Item[1]		Corn	Corn Gluten Meal	Corn Gluten Feed	Germ Meal (db)	DDGS[2]	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[3]		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[4]		9.0	14.0	--	--	44.0	55.0	--	--
LC[5]		3.0	5.0	--	--	18.0	13.0	--	--
C Fiber		2.9	2.2	9.7	13.1	9.9	6.7	--	--
Calcium		0.03	0.16	0.36	0.04	0.15	0.05	0.45	0.018
Pottasium		0.37	0.03	0.64	0.31	0.44	0.65	2.32	0.54
Magnesium		0.14	0.06	0.36	0.34	0.18	0.26	0.69	0.18
Sodium		0.03	0.10	1.05	0.08	0.57	0.09	0.23	0.045
Phosphorus		0.29	0.50	0.82	0.34	0.71	0.57	1.52	0.54
Sulfur		0.12	0.39	0.23	0.33	0.33	0.03	0.74	0.50
Zinc	(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		

Source: National Research Council (1980).
Notes: [1] Composition data for syrup and wet grains from unpublished data.
[2] DDGS = distillers dried grains with solubles.
[3] EE = ether extract.
[4] CW = cell wall material.
[5] LC = lignocellulose.

warmer weather, Consequently, use of wet DDGS is limited to producers located close to the dry grind plant.

While DDGS is the main coproduct that dry grind plants market, they occasionally market syrup (condensed distillers solubles; Figure 3). 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 it is not economical to ship, so its use is limited to local producers. Syrup typically contains 25% to 35% dry matter; solids contain 40 g protein, 15 g ash, 20 g fat and 25 g other material per 100 g (Table 3). Concentrations of many elements, such as sodium, potassium 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 (Belyea *et al.*, 2006).

Wet grains sometimes are marketed by processors for use in primarily ruminant animal diets due to high crude fiber content. There are limited data on nutritional profiles of wet grains. Wet grains were characterized by National Research Council (1980) 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 it is representative of modern dry grind processing. Limited data from our laboratory is suggestive that wet grains have lower fiber and higher protein (30%) and higher fat (13%) than wet grains data reported in National Research Council (1980). Mineral concentrations of wet grains appear to be low (eg, 0.11% calcium (Ca), 0.43% P, 0.18% K; National Research Council 1980).

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 should reflect the interests of both

Table 4: Equivalent Nutrient Value ($/ton) of Ethanol Coproducts for Various Corn and Soybean Meal Prices.

Corn	Soybean Meal	DDGS[1]	Corn Gluten Feed	Corn Gluten Meal
2.50	200	157	133	246
3.00	200	165	148	242
4.00	200	180	178	232
2.50	300	211	156	376
3.00	300	218	171	372
4.00	300	234	200	362
2.50	400	264	178	507
3.00	400	272	193	502
4.00	400	288	223	493

Source: Byproduct Feed Bulletin Board (2003).
Note: [1] DDGS = distillers dried grains with solubles.

ethanol processor and end user (animal producer). However, since ethanol is the 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 or 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 coproduct 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 economical dietary ingredient(s). This places competitive pressure on the marketing of ethanol coproducts to provide a high value coproduct relative to its cost.

The chemical composition of many coproducts can vary markedly, which has been documented by Arosemena *et al.*, 1995; Belyea *et al.*, 1989, 2004; Rausch *et al.*, 2003; 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 points 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 could contain excess protein. It would be possible for ruminants consuming the resulting diet to consume 0.5 to 1.0 pound (lb) excess protein per animal per day. This wastes 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, as 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, 2004; Clevenger *et al.*, 2004; Shurson *et al.*, 2001) have shown the contemporary analytical data for many coproducts differ substantially from published sources, such as National Research Council (1980).

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 microgram (μg) P/liter (L) or higher (Belyea *et al.*, 2006). 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.

Managing the phosphorus content of diets is one method of reducing the phosphorus in animal wastes. Phosphorus contents of most corn processing coproducts range from 5.4 to 8.2 g P/ kilogram (kg) db, which is high relative to common grains and to requirements of most ruminants (Table 3). 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.

New Technologies to Modify the Dry Grind Process

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 (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.*, 2001, 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.

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 4), 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 this fiber component, in addition to germ and 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 dry grind corn processing plant with the enzymatic dry grind process were estimated at \$2 million, or \$11 million additional cost

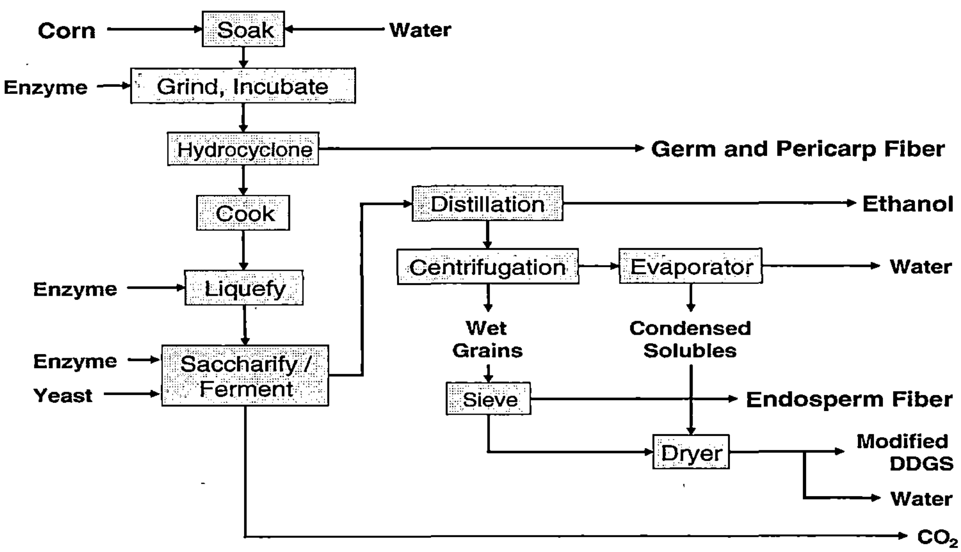

Figure 4: The Enzymatic Dry Grind Process.

Table 5: DDGS Composition (Percent Dry Basis) and Coproduct Values for Conventional Dry Grind and E-Mill Processes.[1]

Composition	Dry Grind	E-Mill	Corn Gluten Meal	Soybean Meal
Crude Protein	28.5	58.5	66.7	53.9
Crude Fat	12.7	4.5	2.8	1.1
Ash	3.6	3.2	--	--
Acid Detergent Fiber	10.8	2.0	6.9	6.0
Coproduct Value				
Germ value[2] ($/ton)	--	242		
DDGS value[3] ($/ton)	136	216	238	202

Notes: [1] Source: Singh *et al.*, 2005.

[2] Market value based on estimates calculated from Johnston *et al.* (2005).

[3] DDGS = distillers dried grains with solubles. Break even prices based on USDA, Economic Research Service values (1994-2004) of corn ($83.92/ton), 50% soybean meal ($191.16/ton) and calculations from Byproduct Feed Bulletin Board (2003) and Howard and Shaver (1997).

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 corn gluten meal (CGM) and soybean meal.

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 58% protein (db) for enzymatic dry grind (Table 5). Break even prices of DDGS are increased from $136/ton for the conventional dry grind process to $216/ton for enzymatic dry grind, using methods to estimate nutritional value (Howard and Shaver, 1997).

The germ fraction recovered from enzymatic dry grind has quality that can be used for oil extraction and contains 35% to 40% oil (db), similar to oil content found in germ recovered using wet milling. The value of germ recovered by the enzymatic dry grind process is estimated to be $242/ton (Table 5; 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 (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 $211/ton (Economic Research Service, 2007). In dry milling, recovered germ will be worth $116 to $137/ton, which is similar to the historical value of DDGS in the conventional dry grind process ($105/ton). 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.

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 low value, 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 affected 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 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 continued expansion expected in the ethanol industry over the next 5 to 10 years, additional work is needed to develop ethanol and coproduct production technologies that mutually meet economic, nutritional and environmental concerns.

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