Ethanol Processing Co-Products: Economics, Impacts, Sustainability

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The production of corn-based ethanol in the United States is dramatically increasing; as is the quantity of co-products generated from this processing sector. These streams are primarily utilized as livestock feed, which is a route that provides ethanol processors with a substantial revenue source and significantly increases the profitability of the production process. With the construction of many new plants in recent years, it is imperative to augment current uses and to find new outlets for these materials, in order to maintain the economic viability of this industry. Known collectively as distillers grains, these residuals have much potential for value-added processing and utilization in other sectors, but barriers currently exist. The goal of this article is to discuss five such constraints and opportunities: storability and handling, value-added livestock and other animal-feed use, human-food use, nontraditional processing into manufactured products, and potential use as sources of bioenergy. Addressing these issues will be essential to the growth of the industry, both in terms of developing new and refined methods for storing and handling these materials, and in identifying and developing new market opportunities for them. Ultimately, alleviating these constraints and pursuing these new possibilities will improve manufacturing economics and can augment the viability of the corn-based fuel-ethanol industry.

DDG Challenges

Currently, the US fuel ethanol industry's only outlet for the nonfermentable residues resulting from the manufacturing process has been utilization as livestock feed. This approach to utilization is well established, but as the ethanol industry continues its rapid growth, and as the generated quantities of these distillers grains increase over time, this avenue needs to be augmented if it is to retain, or even increase, its current high-value economic returns.

Indeed, a host of issues surrounds the value and utilization of distillers grains, both from the ethanol production standpoint, and from a livestock-feeding perspective. Some of the most pressing include:

- the large quantities of energy required to remove water coupled with the high cost of energy; moving distillers dried grains with solubles (DDGS) to diverse and distant markets when there are fluctuations in supply and demand;
- how to avoid mycotoxin contamination;
- variability in nutrient content, quality, and associated quality-management programs, which ultimately impact end-users;
- lack of an industry-wide quality-grading system;
- inconsistent product identity and nomenclature;
- lack of standardized laboratory testing procedures;
- lack of education and technical support for the industry;
- international marketing and export challenges; and
- lack of a national byproduct organization to address these issues and spearhead marketing efforts for these co-products.

Indeed, a question that inevitably arises is, "What are we going to do with all of the DDGS?" These are discussed in more depth by Rausch and Belyea (2006), Rosentrater and Giglio (2005), Rosentrater (2006a) and UMN (2007).

A persistent barrier to effective distillers grains utilization is product storability and flowability—so much so that it has serious economic implications for ethanol plants. Opportunities to increase potential economic returns also include processing DDGS into high-value animal feeds, human foods and industrial composites. To date, however, very little has been published in the scientific literature addressing these four topics. These are all fertile areas for research, but a reference base from which to work is needed. They have tremendous implications for the successful growth of the industry.

STATUS OF THE US FUEL ETHANOL INDUSTRY—2007

With growing energy requirements, coupled with an increasing reliance on nonrenewable fossil fuels, markets for which have historically been quite volatile, the energy security needs of oil importing nations, including the United States, continue to escalate (EIA AEO, 2007). Biofuels—renewable sources of energy—can help meet these increasing needs, and can be produced from a variety of biomass materials including residue straw, corn stover, perennial grasses, legumes, and other agricultural and biological materials. At this time, however, the most heavily utilized substrate in the United States is corn starch. Although directly tied to the market value of the grain itself, fuel-ethanol production from corn is readily accomplished at a relatively low cost *vis-à-vis* other biomass sources. In fact, it is currently the only biological material that can be economically converted into ethanol on an industrial scale. The number of corn-ethanol plants, and their processing capacities, has been markedly increasing in recent years. At the beginning of 2007, for example, 110 manufacturing plants in the United States have an aggregate production capacity of 5.5 billion gallons per year (20.8 billion liters per year). Moreover, seventy-six plants are currently under construction or expansion, and upon completion will contribute an additional 5.6 billion gallons per year (21.2 billion liters per year) (BBI, 2007; RFA, 2007a). As the ethanol market segment continues to grow, so do the quantities of processing residues, or co-products, that are generated.

In-depth details on ethanol manufacturing, which are beyond the scope of this discussion, can be found in Tibelius (1996), Dien *et al.* (2003), Jaques *et al.* (2003), Maisch (2003), Bothast and Schlicher (2005) and Weigel *et al.* (2005). Briefly, ethanol production from corn grain can be accomplished by wet-mill processing, which is very capital intensive, or dry-grind processing, which has substantially less capital and operational requirements, and thus has rapidly gained prevalence in the industry. The dry-grind production process (Fig. 1) consists of several key steps, including grinding, cooking, liquefying, saccharifying, fermenting, and distilling. Typically, there are three main products from a dry-grind facility:

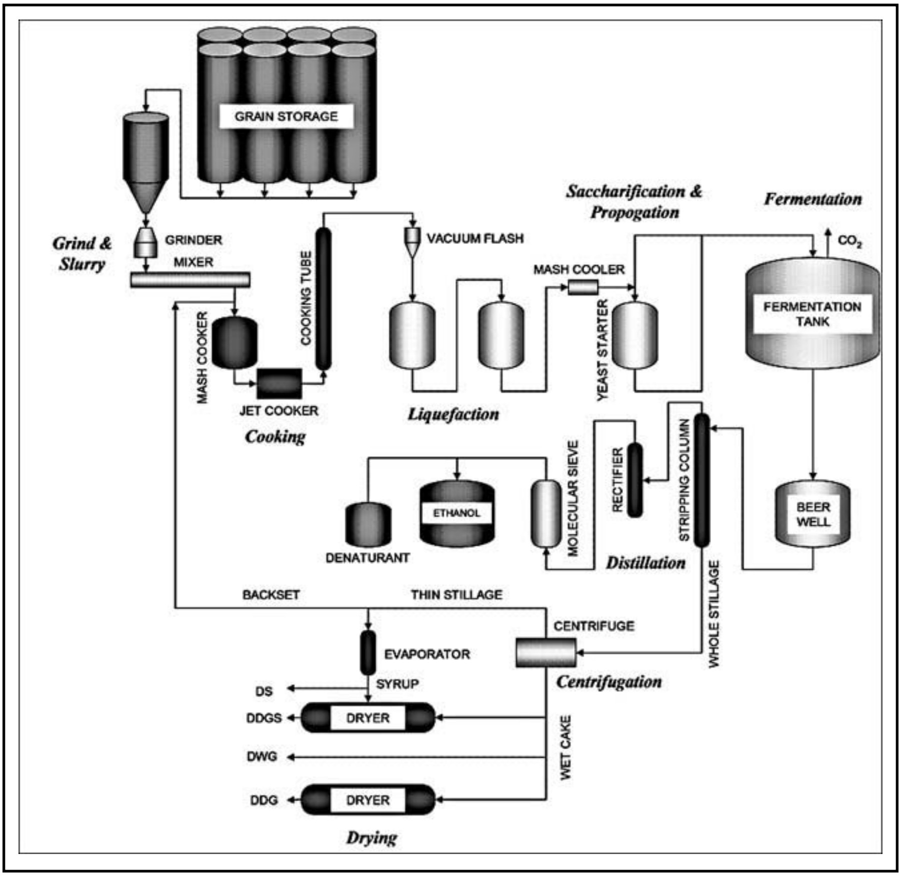

Figure 1. Process flow diagram of a typical dry grind corn-to-ethanol manufacturing plant.

- ethanol, the primary end product (approximately a third of the original corn mass);
- residual nonfermentable corn kernel components (approximately a third of the original corn mass), marketed primarily in the form of DDGS (Fig. 2), and to a lesser degree in the form of distillers dried grains (DDG), which do not contain added solubles, distillers wet grains (DWG; Fig. 3), and condensed distillers solubles (CDS; Fig. 4) (hereafter "distillers grains" will be used in a generic sense to refer to all of these residual materials); and
- carbon dioxide (approximately a third of the original corn mass).

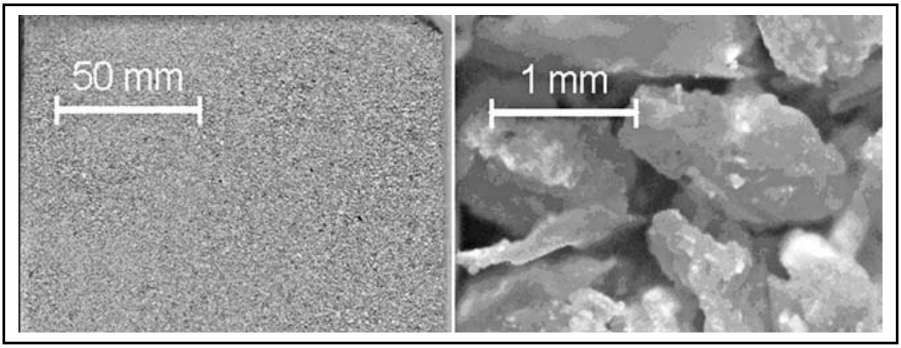

Figure 2. Solid non-fermentable residues—distillers dried grains with solubles (DDGS).

Figure 3. Solid non-fermentable residues—distillers wet grains (DWG).

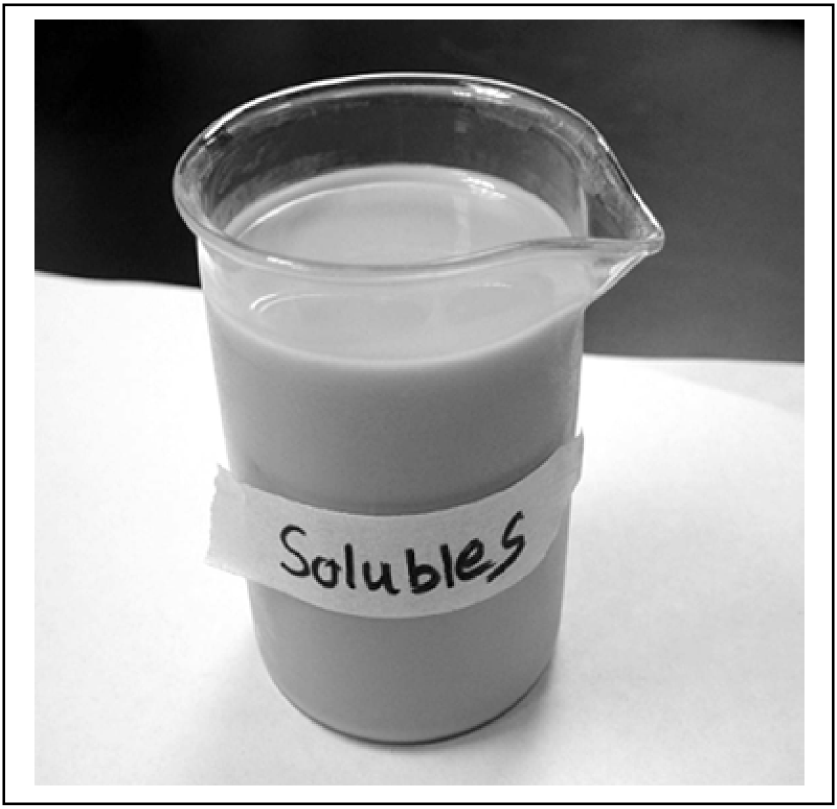

Figure 4. Liquid non-fermentable residues—condensed distillers solubles (CDS).

Residue streams are separated from the ethanol during distillation. They are often dried to approximately 10% moisture content, to ensure a substantial shelf life, and then sold as distillers grains (generally DDG or DDGS) to local livestock producers or shipped via truck or rail to distant livestock feed markets. The sale of distillers grains contributes substantially to the economic viability of ethanol manufacturing (up to $0.10 per liter of ethanol produced, depending on DDGS sales price), and is thus a vital component to each plant's operations. Because of the dynamics of the free-market economy, as this industry continues to grow the quantity of processing residues—and the ability to utilize them—will, in turn, significantly impact the future of the industry.

Historically, the ethanol industry's only outlet for non-fermentable residues has been as livestock-feed ingredients. This approach is well established, but needs to be augmented and optimized if it is to retain its high-value returns, especially as the generated quantities of these residues increase. Increased supply of distillers grains will affect the potential sales price *vis-à-vis* feed demand, which could severely impact the production economics of the industry in the near future. In order to address these challenges, the ethanol industry needs a diversified utilization strategy, instead of the current unidirectional approach. If estimates of future ethanol production hold true, utilization as livestock feed alone may not prove to be sustainable and thus alternative avenues must be pursued. Potential routes should include value-added animal feeds, human foods, and industrial products. One of the major hurdles that must be addressed (even prior to developing these new uses) is to improve the storage and handling characteristics of these materials.

Storage, Handling, and Flowability Challenges

With the exponential growth of the fuel-ethanol industry in the past several years, substantial quantities of distillers grains are now being produced, and even more are anticipated in the foreseeable future. To utilize these as feeds, however, these materials are increasingly being transported greater distances via truck and rail, and must be stored in various structures, such as bins and silos, until final use. Unfortunately, discharge flow is often problematic, due to caking and bridging between particles, which frequently occurs during storage and transport. In fact, flowability has become a major issue to be addressed for effective sales, marketing, distribution, and utilization of distillers grains (Rosentrater and Giglio, 2005; Schlicher, 2005; Rosentrater 2006b). For example, because these co-products do not easily flow from rail cars, in order to induce flow, workers often hammer the car sides and hopper bottoms. This leads to severe damage to the rail cars themselves, repairs of which have become very expensive to ethanol-manufacturing companies. Large carriers, such as the BNSF and UP railroads have even prohibited DDGS shipments.

Even though anecdotal knowledge regarding flowability is present in the industry, it is often incomplete and proprietary in nature. Furthermore, no formal scientific studies have yet investigated handling or flow properties of distillers grains. From studies of other granular materials, though, it is probable that flowability problems may arise from a number of synergistically interacting factors, including product moisture, fat content, particle size distribution, storage temperature, relative humidity, time, compaction pressure distributions within the product mass, vibrations during transport and/or variations in levels of these factors throughout the storage process (Craik and Miller, 1958; Johanson, 1978; Moreyra and Peleg, 1981; Teunou *et al.* 1999; Fitzpatrick *et al.*, 2004a, 2004b).

Generally speaking, flowability is defined as the ability of granular solids and powders to flow. It is, in fact, not an inherent natural material characteristic, but rather is the consequence of several interacting properties that simultaneously influence material flow, environmental conditions, and the equipment used for handling, storing, and processing (Prescott and Barnum, 2000). Flow behavior is thus multidimensional, depending on many physical and chemical characteristics. Because of this, no single test can quantify a product's flowability; instead a suite of tests is required. In addition to the factors listed above, other properties that affect flowability can include protein, starch, and carbohydrate levels, as well as addition of flow-conditioning agents (Peleg and Hollenbach, 1984).

Knowledge of physical and flow characteristics of bulk solids is essential for the design of reliable storage systems and handling equipment. Toward this end, shear testers are the primary equipment used to measure the strength and flow properties of granular materials. A shear test consists of two stages: measurement of consolidation (*i.e.*, compaction over time) and determination of particle strength. The measured strength depends on the degree of consolidation, and how it was achieved (*i.e.*, stress history). Each of these aspects is highly dependent upon the other (Schwedes, 2002). It has been found that stress history and anisotropic behavior have a strong influence on the particle strength of a bulk solid. It has also been concluded that a reliable prediction of the strength of a bulk solid can be achievable only if the stress history, and the directions of the major principal stresses during consolidation and failure, are known for specific applications.

Jenike (1964) developed the fundamental method for determining these flow characteristics. To analyze flow in bins and hoppers, and to develop a flow/no-flow criterion for various materials, Jenike used the principles of plastic failure with the Mohr-Coulomb failure criteria (Thomson, 1997). From a physical standpoint, the general principle is that granular flow is equivalent to solid failure due to shear. In ideal, free-flowing materials, resistance to flow is only the result of friction; in cohesive materials, however, inter-particle forces are enhanced by compaction, which can, in turn, produce mechanical strength and, thus, flow resistance (Peleg, 1983). Over the years, Jenike's direct shear cell tester and associated methodologies have become benchmarks for determining appropriate industrial design criteria for storage bins and silos. Jenike's shear cell has been used by many researchers for characterizing various granular materials. For example, the shear cell has been used to study the flow properties of various powders (Ashton *et al.*, 1965), cement (Schrämli, 1967), fine lactose powder with and without flow conditioners (York, 1975), wheat flour and sugar (Kamath *et al.*, 1993), wheat flour (Kamath *et al.*, 1994), confectionary sugar and detergent (Duffy and Puri, 1994), grains (Duffy and Puri, 1999) and milk powders (Fitzpatrick *et al.*, 2004b).

Carr (1965a, 1965b) also developed a number of standard procedures that permit the evaluation of flowability of granular materials, involving the determination of four main physical properties: angle of repose, compressibility, angle of spatula, and coefficient of uniformity (*i.e.*, cohesion). It does not, however, account for consolidation or stress history. Even so, the information determined by this methodology is also extremely useful for designing bins and hoppers so that appropriate material handling and particle flow can be achieved. This is especially true when used in conjunction with Jenike shear data.

Even though the Jenike and Carr procedures are commonly used in industry, to date no formal studies have investigated handling or flow properties of distillers grains. Determining the specific physical or chemical factors, or interactions thereof, that cause flowability problems for these materials should be undertaken, because solving this problem will have substantial economic ramifications throughout the fuel-ethanol industry. Storage and handling operations must be improved *vis-à-vis* current technologies and practices, especially as sales and distribution of these materials move beyond regional areas and become more national in scope. Preliminary studies in our laboratory indicate that consolidation may very well be a main contributor to many flowability problems observed in distillers grains; the other synergistically acting factors, however, remain to be analyzed and quantified.

VALUE-ADDED ANIMAL FEEDS

As with many food and organic processing residue streams, feeding distillers grains to livestock is a viable method of utilization because of their high nutrient levels. Over the years, numerous research studies have been conducted in order to assess co-product use as animal feed, including investigations focused on beef rations (Firkins *et al.*, 1985; Ham et al., 1994; Lodge *et al.*, 1997; Peter *et al.*, 2000 Al-Suwaiegh *et al.*, 2002), dairy diets (Nichols *et al.*, 1998; Powers *et al.*, 1995; Schingoethe *et al.*, 1999; Hippen *et al.*, 2004; Kalscheur *et al.*, 2004), swine rations (Wahlstrom *et al.*, 1970; Cromwell *et al.*, 1993; Noblet *et al.*, 1994; Gralapp *et al.*, 2002; Shurson *et al.*, 2004; Whitney and Shurson, 2004), and poultry diets (Waldroup *et al.*, 1981; Parsons *et al.*, 1983; Noll *et al.*, 2002; Ergul *et al.*, 2003; Lumpkins *et al.*, 2003; Roberson, 2003). Aines *et al.* (1986) and UMN (2007) provide comprehensive reviews of this research.

But, much additional research must be done in order to maximize the inclusion of these residues in animal feeds, especially in light of the fact that as the processes employed in the industry evolve, the resulting quality and composition of the co-products thus continue to change. Distillers grains are often used in beef and dairy rations and, to a lesser extent, in swine and poultry diets; aquaculture feeds and pet foods are two market segments that are, as yet, untapped.

Protein-rich DDGS from ethanol plants have been used as livestock feed for many years. Feed conversion efficiency in fish, however, is typically much higher compared to traditional livestock. The cost of processing fish feed is one of the challenges for profitable fish cultivation. Due to the exponential increase in number of ethanol plants in recent years, though, DDGS are becoming readily available as a reasonably priced base material. And because they have a relatively high protein content, they may have potential as a fish-feed substitute for fish meal. Even though much literature is available on incorporation of distillers grains into the diets of various livestock species, very little has been accomplished in the aquaculture arena. Fish require unique physical and functional properties compared to other animal feeds (such as specific nutritional profiles). Additionally, pellet floatability is essential to many fish species; this can generally be achieved via extrusion processing. To date, only a little research has been carried out on utilizing DDGS as a protein source in aquaculture feed; limited work has investigated feeding trout, tilapia, prawns and catfish (James *et al.*, 1993; Webster *et al.*, 1993; Wu *et al.*, 1996, 1997; Cheng and Hardy, 2004a, 2004b; Cheng *et al.*, 2003; Coyle *et al.*, 2003, 2004). These studies have found that DDGS, in combination with other feed ingredients, could partially or even totally replace fish meal as a protein source, and that fish-growth performance could be maintained at acceptable levels.

Much work remains to improve and maximize the utilization of these co-products in animal feeds, both for ruminants as well as for mono-gastric species. Five key priorities must be addressed:

- densification, via pelleting or cubing, of DDGS streams and/or specific fractions in order to improve the bulk density, storability, transportation, and delivery for animal utilization—essential considerations include pellet compressibility, durability, digestibility, and other physical and nutritional properties of the densified feed products;

- processing of DDGS streams and/or specific fractions into value-added feed products, including aquaculture feeds and pet foods, which are untapped market segments and have much potential for growth;
- processing of DDGS streams and/or specific fractions with other relatively low-value processing/organic waste streams, in order to augment nutritional contents and produce novel feed ingredients;
- quantifying and enhancing storability, shelf life, and preservation of these resulting feed products (especially wet products); and
- feeding, growth performance, and acceptability testing of these novel feed products.

Preliminary trials in our laboratory indicate that extrusion processing is a promising technology for achievement of many of these priorities.

Human Foods

Historically, the benefits of diets containing high levels of dietary fiber have become well documented, including lowering of serum cholesterol levels, blood pressure, risk of heart disease, chance of various cancers, and improved weight loss/control (Burkitt, 1977; Anderson *et al.*, 1987; Anderson *et al.*, 1994; Mehta, 2005). Recently, diets that also contain low levels of carbohydrates (especially starch), such as the Atkins (Atkins, 1992) and South Beach diets (Agatston, 2003), have also become popular (Angelich and Symanski, 2004; Sloan, 2004; Hursh and Martin, 2005). Not only do diets that contain high fiber and low starch promote weight loss and control, but current research into glycemic response and resulting after-meal satiety indicates that these diets also have substantial health benefits for diabetic patients as well as those suffering from obesity (Li *et al.*, 2003; Brand-Miller, 2004; Gross *et al.*, 2004; Hofman *et al.*, 2004; Layman and Baum, 2004; Rendell *et al.*, 2005), not only for blood-sugar control in diagnosed patients, but also for prevention of diabetes and obesity onset. Because distillers grains are high in fiber and low in starch, they have potential for use in such dietary regimes.

Over the years, several studies have examined distillers grains as functional ingredients for human foods, including Bookwalter *et al.* (1984), Wall *et al.* (1984), Kim *et al.* (1989), Maga and Van Everen (1989), Rasco *et al.* (1990), Abbott *et al.* (1991), Brochetti *et al.* (1991) and Van Everen *et al.* (1992). These, and other prior investigations into use of distillers grains as food ingredients, have been thoroughly compiled and reviewed by Rosentrater and Krishnan (2006). Most prior studies have focused primarily on breads and cookies. To a lesser extent, other food products, including pastas, blended ingredients, extruded products and other miscellaneous food items have also been investigated. As Rosentrater and Krishnan (2006) have discussed, incorporation of distillers grains has generally been shown to impact the resulting organoleptic quality of food products, especially as inclusion/substitution rates increase. Most food products become darker in appearance when distillers residues are included. Most of the products studied indicated a decreased functionality compared to the original components replaced by distillers grains, including resulting volume and expansion during baking, moisture absorption, texture, and mouth-feel. Moreover, products incorporating distillers byproducts at relatively high inclusion levels have shown a definite impact on flavor and are typically rated as marginally acceptable to not acceptable at all. Poor flavor could be improved, though, by bleaching and deodorizing prior to inclusion in the food matrix, because fatty acids that influence off-flavor development can be neutralized. Because of these challenges, it is not surprising that there is currently no commercial food product that incorporates ethanol-processing co-products.

As a direct result of the energy crises of the 1970s, the US fuel-ethanol industry began a slow but steady growth. Development of food products from distillers grains from this industry is not a new concept. In the 1980s, twenty-three studies were conducted and forty-seven food products were investigated. After the 1980s, the ethanol industry continued to grow, but interest in food products from distillers co-products waned considerably. In the 1990s, only eight studies were conducted and ten products investigated; in the 2000s, however, only one study and five products have been investigated thus far. As a result of this decline in interest, the lack of product-development work in last 15 years has become a hindrance to the utilization of distillers grains in food products, especially in light of the changes that these residues have undergone during this time period.

Numerous manufacturing improvements and process modifications have been realized over these years, particularly with the advent of the corn dry-grind production process. Now many of these "next generation" plants are in operation, and, in fact, comprise almost 80% of the entire industry (RFA, 2007a,b). Moreover, many additional dry-grind facilities are currently under construction. Dry-grind plants produce distillers grains with considerably different nutrient contents and physical properties from those produced by their predecessors—the corn wet mills of the 1980s (Spiehs *et al.*, 2002; Rosentrater *et al.*, 2005). As this industry continues to expand, many ethanol plants are increasingly interested in construction and operation at food-grade status, in order to expand the opportunities for utilization of distillers grains beyond traditional livestock feed. But, they do need market outlets for these new materials in order for this pursuit to succeed. Thus, a dedicated product-development initiative needs to address and optimize the use of these new processing residues, especially DDGS.

In order for viable food products to be successfully manufactured and marketed, considerable research is needed:

- analysis of current commercial DDGS streams and/or specific fractions for food-grade applicability, especially nutritional contents and chemical levels, including vitamins, minerals, nucleic acids, pigments, heavy metals, and toxic and other compounds that may be present;
- methods for processing and upgrading DDGS streams and/or specific fractions into food-grade ingredient streams, including:
  - various pretreatments, such as separation and concentration of proteins, fibers, lipids, or other compounds,

  - washing, cleaning, and other quality-upgrading steps,
  - bleaching,
  - deodorizing,
  - drying,
  - sterilizing,
  - milling into corn flour,
  - storage stability and preservation, and
  - analysis of any residues that result from these upgrading steps;
- nutritional enhancements that may be necessary to improve functionality, flavor and utilization potential;
- developing specific, marketable food products such as bakery goods, noodles, pastas, or other low-starch/high-protein/high-fiber foods;
- quantifying storability, shelf life and preservation of these resulting food products; and
- sensory analysis and acceptability testing of the resulting food products.

Manufactured Products

Beyond the realms of traditional livestock feed and potential human-food ingredients, very little work has been undertaken to develop other value-added applications for ethanol-residue streams. Initial trials have been conducted using these co-products as soil amendments and fertilizers (Erdem and Ok, 2002; Ramana *et al.*, 2002a, 2002b), extracting oil to produce industrial compounds and chemicals (Singh and Cheryan, 1998; Singh *et al.*, 2001; Kwiatkowski and Cheryan, 2002; Singh *et al.*, 2002), and extrusion processing (Rai et al., 2004). Although manufacturing of distillers grains into industrial products is currently an untapped area, it is a potentially high-value avenue that should be pursued.

Modern manufacturing involves complex interactions among many factors, including product design, raw materials, manufacturing processes, as well as product distribution and sales. Thorough overviews of these topics have been provided by Creese (1999), Kalpakjian and Schmid (2001) and Geng (2004). In recent years, interest has grown in incorporating non-traditional, biological materials into traditional manufacturing operations to produce high-quality, cost-competitive, biodegradable finished products.

Progress in industrial biomaterials has accelerated in the last few decades as environmental consciousness has increased and production processes have become more efficient. A wide variety of viable bioproducts are produced industrially (Aberg *et al.*, 2002; Gandini and Belgacem, 2002), ranging from processing biomaterials into completely biobased finished products to utilizing them as additives or reinforcements in composites (Mohanty *et al.*, 2002). Available literature shows diverse applications, including biomedical (*e.g.* degradable protein sutures and implants), food-processing containers, packaging materials and structural members, to name only a few. The three product categories that currently encompass the greatest number of viable biomaterials, however, are films, foams and composites.

Because of disposal problems with conventional films, many studies have targeted development of biodegradable counterparts (Thring *et al.*, 1997; Godbole et al., 2003; Kayserilioglu *et al.*, 2003; Intabon *et al.*, 2004; Kumar *et al.*, 2004; Wang *et al.*, 2004b; Zhang and Whistler, 2004; Imam *et al*, 2005), using compounds found in biological materials, such as alginic acid, arabinoxylan, cellulose, chitin, curdlan, lignin, soy protein, starch, xanthan, xylan, whey and zein. Biofilms are currently used in many products, including agricultural applications, such as landscaping and greenhouse construction (Briassoulis, 2004a, 2004b), as well as coating and packaging materials (Li and Chen, 2000). In addition to biodegradability, many of these studies have reported improved toughness and tensile strength by the inclusion of biological materials. Preliminary data indicate that distillers grains are a potential source of concentrated zein, which could be used for film production, although the functional state of these molecules is not yet known.

As most ultimately end their service lives in landfills, foams represent another area where biodegradability would be a tremendous asset. Biological materials have been used in a variety of insulation, packaging, and buoyancy products. Many foaming-development studies have been conducted using a host of biological materials, including wood fibers, starch, corn-stover fibers, and soybean oil (Fang and Hanna, 2000; Guo *et al.*, 2003; Ganjyal et al., 2004; Javni et al., 2004; Lee et al., 2004). Many of these foams, however, although completely biodegradable, do not have sufficient mechanical strength and lack water resistance, both of which are barriers to widespread use. To address this, Fang and Hanna (2001) added degradable co-polyester to improve starch properties; the resulting foams exhibited water resistance and excellent resiliency against deformation while maintaining biodegradability. These foams were comparable to traditional polystyrene, which is not biodegradable and has limited recyclability. Preliminary studies in our laboratory indicate that distillers grains can be utilized to produce biodegradable foams as well; these trials have indicated excellent foaming and final-product properties, and thus warrant further study.

The third main category of use, composite products, encompasses a broad array of materials. Much research has been conducted in recent years (Lammers and Kromer, 2002; Colom *et al.*, 2003; Jayaraman, 2003; Keller, 2003; Lundquist *et al.*, 2003; Pothan *et al.*, 2003; Joshi *et al.*, 2004; Julson *et al.*, 2004; Wang *et al.*, 2004a). In addition to the production of finished biobased products, many biological materials have also been used to improve the physical and mechanical properties of conventional plastics. Examples cited in the literature often involve alternative use of residue materials produced in large quantities (*e.g.*, as a result of agro processing), as well as specific biomass crops grown for dedicated use in biomaterials: bagasse (Chiellini *et al.*, 2004; Rout *et al.*, 2003), flax fibers (Joffe *et al.*, 2003; Baiardo *et al.*, 2004; Wang *et al.*, 2004a), palm fibers (Sreekala and Thomas, 2003; Abu-Skarkh *et al.*, 2004), sisal fibers (Li *et al.*, 2000; Joseph *et al.*, 2003), jute fibers (Ray *et al.*, 2002; Khan *et al.*, 2005), soy products (Ashby *et al.*, 2004; Swain *et al.*, 2004), and corn-processing co-products (Julson et al., 2004; Montgomery, 2004). Many of these studies show that use of biomaterials as fillers can lead to substantially improved properties in the resulting composite plastics. Preliminary experiments in our laboratory indicate that distillers grains can be utilized to produce durable biodegradable composites when injection molded with thermoplastics or compression molded with phenolic resins.

The goals of utilizing biomaterials often include offering alternatives for bioprocessing residues and byproducts, decreasing manufacturing costs and improving final product biodegradability. But, the applicability of a given biomaterial must first be determined before it can be used in an actual manufacturing environment, and its compatibility with specific polymers and resins must be determined before it can be used effectively and economically. Findings of previous studies discussed here, compounded with those of many other researchers in the literature, suggest that the potential for biobased products is continuing to increase, and that more focus on investigating compatibility and methods of manufacture is needed for these materials.

Many potential avenues for utilization of distillers grains beyond feed and food do exist, and should be investigated in order to increase possible value-added uses. Based on our own preliminary laboratory investigations, it appears that distillers grains do have much potential for manufacturing into various biobased products, including films, foams, and composites.

Conclusions

The US corn-based fuel-ethanol industry is currently experiencing unprecedented growth. In conjunction with this expansion, the quantity of distillers grains produced has grown. This industry has continually evolved and technological innovations and process changes have been implemented that have improved process efficiencies, but have also affected the resulting co-product streams. As a consequence, new questions, challenges, and opportunities for utilizing these residues have arisen. As the quantity of these materials continues to grow, it is vital that value-added uses for distillers grains continue to be developed and augmented. Many issues currently face the ethanol industry in this regard. This article has discussed one of these: flowability. Addressing this challenge will have a substantial impact on the industry, as new or improved processes that lead to enhanced DDGS storability and flowability behavior are realized. This article has also reviewed three areas where substantial potential lies for value-added processing and utilization, including animal feeds, human foods, and industrial products. Pursuing these can lead to increased utilization of DDGS, thus preventing saturation of the livestock feeds market with ethanol co-products. Ultimately, addressing the topics discussed in this paper could lead to enhanced economic viability for the entire ethanol industry.

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