7

Overview of Corn-Based Fuel Ethanol Coproducts: Production and Use

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1. Introduction

Modern societies face many challenges, including growing populations, increased demands for food, clothing, housing, consumer goods, and the raw materials required to produce all of these. Additionally, there is a growing need for energy, which is most easily met by use of fossil fuels (e.g., coal, natural gas, petroleum). For example, in 2008, the overall U.S. demand for energy was 99.3 x 10^{15} Btu (1.05 x 10^{14} MJ); 84% of this was supplied by fossil sources. Transportation fuels accounted for 28% of all energy consumed during this time, and nearly 97% of this came from fossil sources. Domestic production of crude oil was 4.96 million barrels per day, whereas imports were 9.76 million barrels per day (nearly 2/3 of the total U.S. demand) (U.S. EIA, 2011). Many argue that this scenario is not sustainable in the long term, and other alternatives are needed.

Biofuels, which are renewable sources of energy, can help meet some of these increasing needs. They can technically be produced from a variety of materials which contain either carbohydrates or lipids, including cereal grains (such as corn, barley, and wheat), oilseeds (such as soybean, canola, and flax), legumes (such as alfalfa), perennial grasses (such as switchgrass, miscanthus, prairie cord grass, and others), agricultural residues (such as corn stover and wheat stems), algae, food processing wastes, and other biological materials. Indeed, the lignocellulosic ethanol industry is poised to consume large quantities of biomass in the future (Agrawal et al., 2007; Alexander and Hurt, 2007; Cassman, 2007; Cassman et al., 2006; Cassman and Liska, 2007; Dale, 2007; De La Torre Ugarte et al., 2000; Dewulf et al., 2005; Lynd and Wang, 2004). At this point in time, however, the most heavily used feedstock for biofuel production in the U.S. is corn grain. Industrial-scale alcohol production from corn starch is readily accomplished, and at a lower cost (generally between $1/gallon and $1.4/gallon), compared to other available biomass substrates in the U.S. The most commonly used process for the production of fuel ethanol from corn is the dry grind process, the primary coproduct of which is distillers dried grains with solubles (DDGS) (Figure 1), which will be discussed subsequently.

Corn-based ethanol has been used as a liquid transportation fuel for more than 150 years, although up until recent times the industry has been quite small. The modern corn-based fuel ethanol industry, however, has reached a scale which can augment the nation's supply of transportation fuels. In 2008, for example, ethanol displaced more than 321 million barrels of oil (Urbanchuk, 2009), which accounted for nearly 5% of all oil imports. Only recently has this industry become truly visible to the average citizen. This has been due, in part, to the growing demand for transportation fuels, escalating prices at the fuel pump, positive economic effects throughout rural America, as well as questions and controversies surrounding the production and use of corn ethanol.

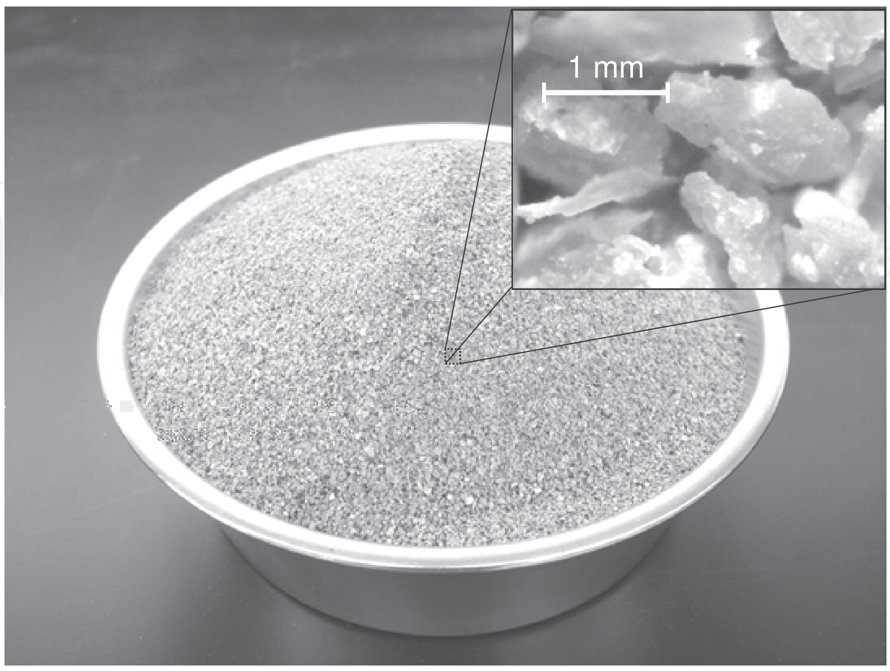

Fig. 1. Corn-based distillers dried grains with solubles (DDGS), which is currently available from most U.S. fuel ethanol plants.

To help meet the increasing demand for transportation fuels, the number of ethanol plants has been rapidly increasing in recent years, as has the quantity of fuel ethanol produced (Figure 2).

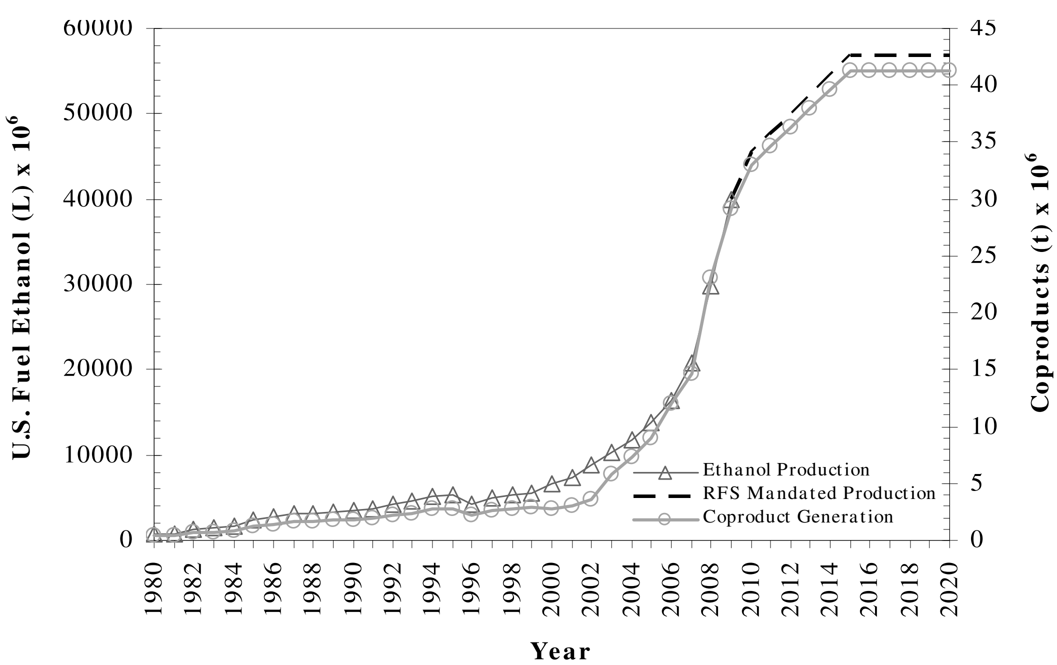

Fig. 2. U.S. fuel ethanol (L) and DDGS (t) production over time; RFS denotes levels mandated by the Renewable Fuel Standard. Inset shows number of U.S. ethanol plants over time (adapted from RFA, 2009a, 2009b, 2011)

In 2005, 87 manufacturing plants in the U.S. had an aggregate production capacity of 13.46 billion L/y (3.56 billion gal/y). At the beginning of 2011, however, that number had risen to 204 plants with a production capacity of nearly 51.1 billion L/y (13.5 billion gal/y), which is an increase of nearly 380% in six years (RFA, 2011). Most new ethanol plants have been dry-grind facilities (Figure 3), which will be discussed subsequently. And, over the next several years, the

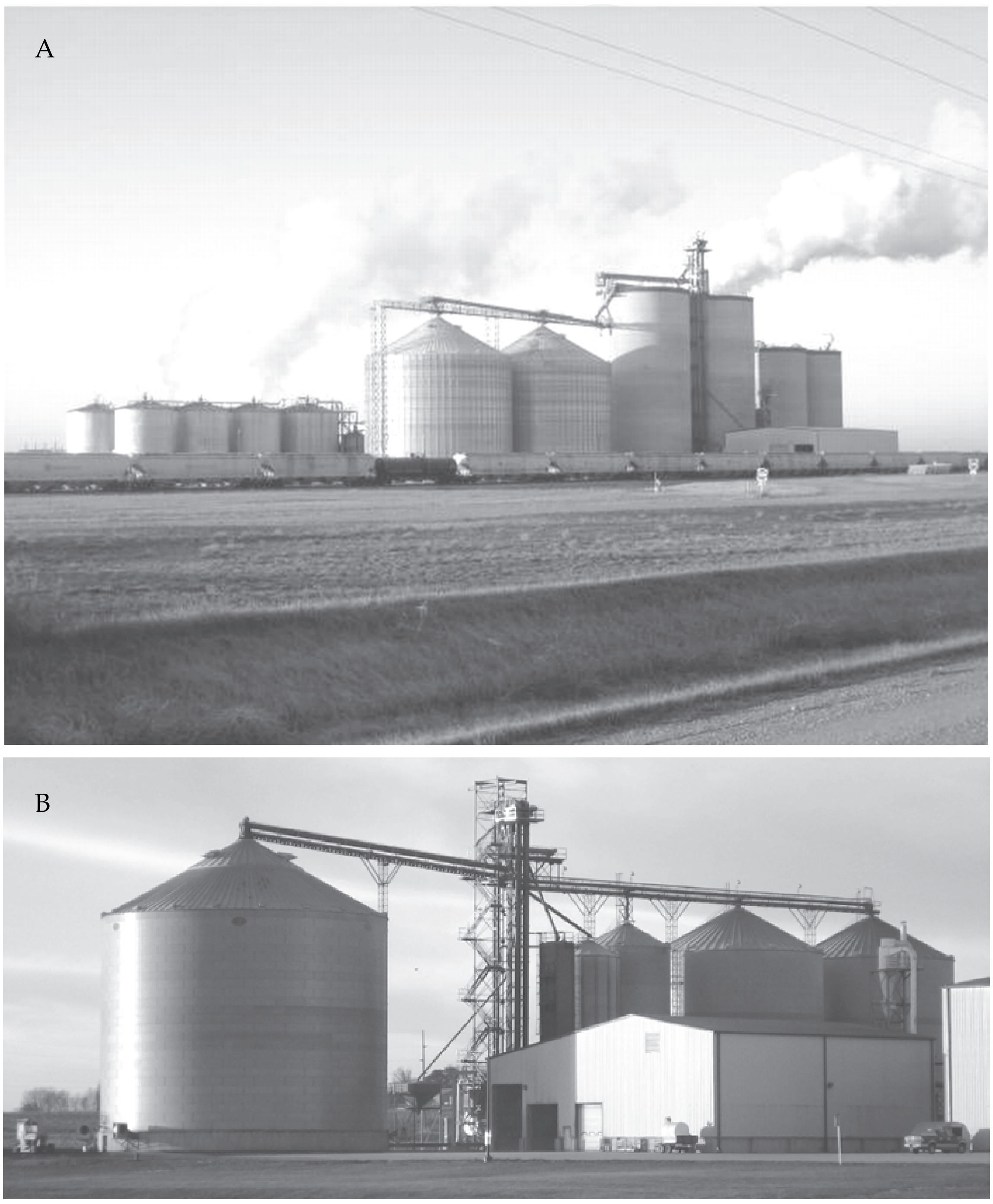

Fig. 3. U.S. dry grind corn-to-ethanol manufacturing plants. A. 450 x 10^6 L/y plant. B. 80 x 10^6 L/y plant.

Renewable Fuel Standard (RFS) mandates the use of 15 billion gal/y (56.8 billion L/y) of renewable biofuels (i.e., which will primarily be corn-based ethanol) (RFA, 2009a), although the RFS does mandate the growing use of advanced and cellulosic biofuels as well. Because the industry is dynamic and still evolving, these current production numbers will surely be outdated by the time this book is published. As production volume increases, the processing residues (known collectively as "distillers grains" –will increase in tandem (as shown in Figure 2). It is anticipated that over 40 million metric tonnes (t) of distillers grains (both wet and dry) will eventually be produced by the U.S. fuel ethanol industry as production reaches equilibrium due to the RFS.

It is true that as the industry has grown, the concomitant consumption of corn has grown as well (Figure 4). Since 2008, for example, over 30% of the U.S. corn crop has been used to produce ethanol. When examining these numbers, however, it is important to be aware of several key points: exports have been relatively constant over time, there has been a slight decline in the corn used for animal feed, and the overall quantity of corn which is produced by U.S. farmers has been substantially increasing over time. Thus, it appears that the corn which is used to produce ethanol is actually arising mostly from the growing corn supply. It is also important to note that the corn which is redirected away from animal feed is actually being replaced by DDGS and other ethanol coproducts in these animal feeds. Thus coproducts (especially DDGDS) are key to the sustainability of both the ethanol and livestock industries. In other words, fuel, feed, and food needs can be simultaneously met.

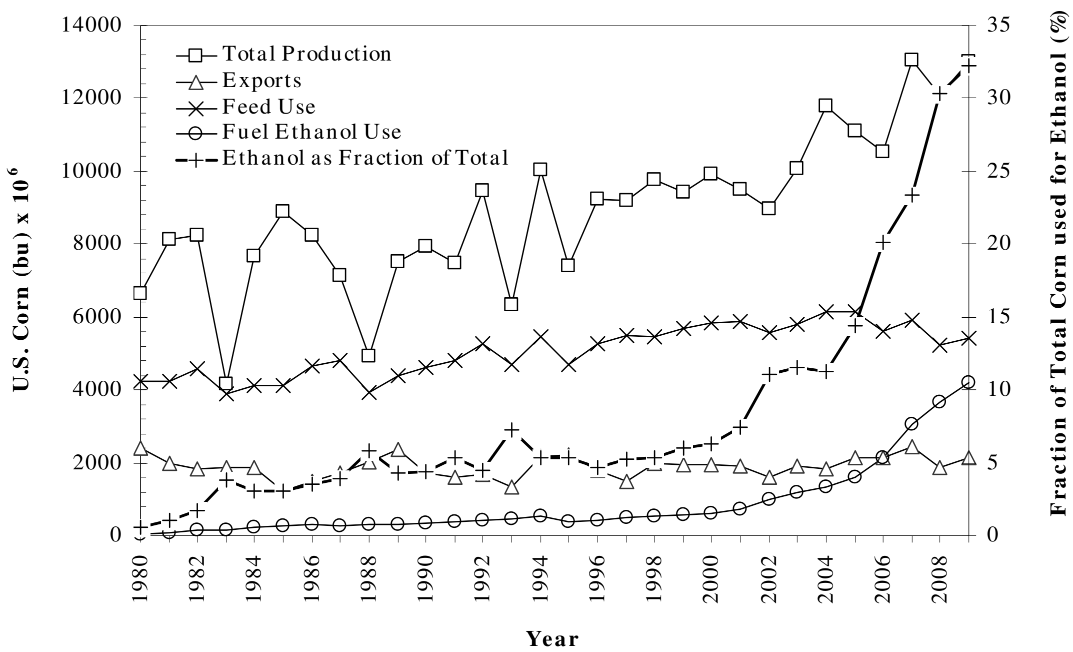

Fig. 4. Historic U.S. corn production (bu) and major categories of use (adapted from ERS, 2011).

2. Objectives

The goals of this chapter are three-fold: 1) to briefly discuss U.S. fuel ethanol and coproduct manufacturing processes; 2) to explain the importance of coproducts to the fuel ethanol and livestock industries; and 3) to describe how coproduct quality is improving and potential uses are expanding as the ethanol industry continues to evolve.

3. Manufacturing processes

Corn can be converted into fuel ethanol by three commercial processes: wet milling, dry milling, and dry grind processing. Over the last decade, many new fuel ethanol plants have been built (Figure 2), and considerable innovations have occurred throughout the industry vis-à-vis production processes used and final products produced, as well as raw materials, water, and energy consumption. Many of these innovations have arisen with the advent of dry grind processing. Due to many advantages, including lower capital and operating costs (including energy inputs), most new ethanol plants are dry grind facilities as opposed to the older style mills. For example, in 2002, 50% of U.S. ethanol plants were dry grind; in 2004 that number had risen to 67%; in 2006 dry grind plants constituted 79% of all facilities; and in 2009 the fraction had grown to over 80% (RFA, 2009a).

The dry grind process (Figure 5) entails several key steps, including grain receiving, distribution, storage, cleaning, grinding, cooking, liquefaction, saccharification, fermentation, distillation, ethanol storage and loadout, centrifugation, coproduct drying, coproduct storage and loadout. Additional systems that play key roles include energy / heat recovery, waste management, grain aeration, CO_2 scrubbing and extraction, dust control, facility sanitation, instrumentation and controls, and sampling and inspection. Figure 5 depicts how all of these pieces fit together in a commercial plant.

Grinding, cooking, and liquefying release and convert the corn starch into glucose, which is consumed during the fermentation process by yeast (Sacchharomyces cerevisiae). After fermentation, the ethanol is separated from the water and nonfermentable residues (which consist of corn kernel proteins, fibers, oils, and minerals) by distillation. Downstream dewatering, separation, evaporation, mixing, and drying are then used to remove water from the solid residues and to produce a variety of coproduct streams (known collectively as distillers grains): wet or dry, with or without the addition of condensed solubles (CDS). Distillers dried grains with solubles (known as DDGS), is the most popular, and is often dried to approximately 10% moisture content (or even less at some plants), to ensure an extended shelf life and good flowability, and then sold to local livestock producers or shipped by truck or rail to various destinations throughout the nation. DDGS is increasingly being exported to overseas markets as well. Distillers wet grains (or DWG) has been gaining popularity with livestock producers near ethanol plants in recent years; in fact, it has been estimated that, nationwide, more than 25% of distillers grains sales are now DWG. But, because the moisture contents are generally greater than 50 to 60%, their shelf life is very limited, especially in summer months, and shipping large quantities of water is expensive. DDGS is still the most prevalent type of distillers grain in the marketplace.

Dry grind ethanol manufacturing results in three main products: ethanol, the primary end product; residual nonfermentable corn kernel components, which are sold as distillers grains; and carbon dioxide. A common rule of thumb is that for each 1 kg of corn processed, approximately 1/3 kg of each of the constituent streams will be produced. Another rule of thumb states that each bushel of corn (~ 56 lb; 25.4 kg) will yield up to 2.9 gal (11.0 L) of ethanol, approximately 18 lb (8.2 kg) of distillers grains, and nearly 18 lb (8.2 kg) of carbon dioxide. Of course, these will vary to some degree over time due to production practices, equipment settings, residence times, concentrations, maintenance schedules, equipment conditions, environmental conditions, the composition and quality of the raw corn itself, the location where the corn was grown, as well as the growing season that produced the corn.

During fermentation, carbon dioxide arises from the metabolic conversion of sugars into ethanol by the yeast. This byproduct stream can be captured and sold to compressed gas markets, such as beverage or dry ice manufacturers. Often, however, it is released to the atmosphere because location and/or logistics make the sales and marketing of this gas economically unfeasible. In the future, however, the release of carbon dioxide may eventually be impacted by greenhouse gas emission constraints and regulations.

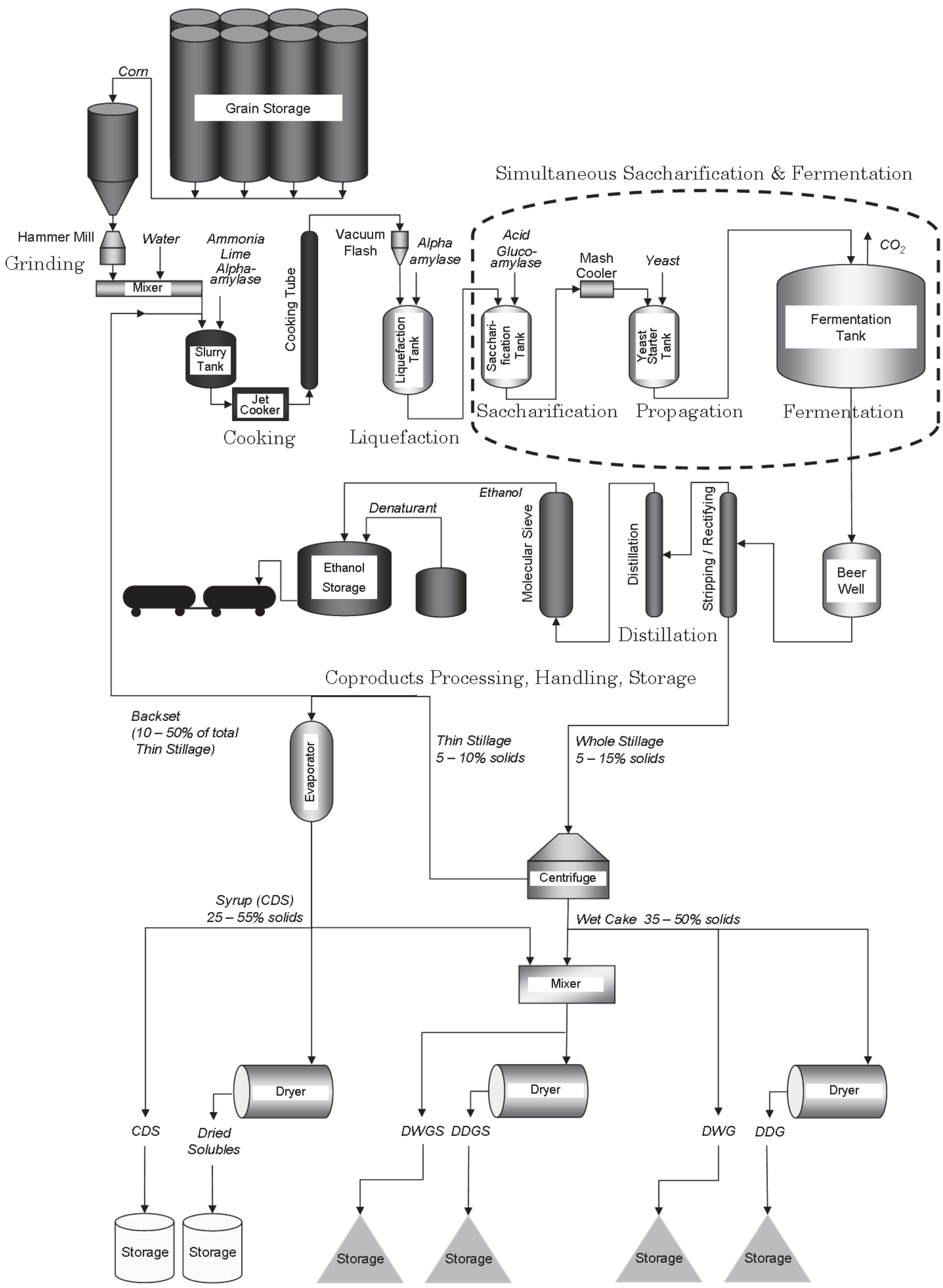

Fig. 5. Flow chart of typical corn dry grind fuel ethanol and coproducts processing.

Additional detailed information on ethanol and DDGS processing steps can be found in Tibelius (1996), Weigel et al. (1997), Dien et al. (2003), Jaques et al. (2003), Bothast and Schlicher (2005), Rausch and Belyea (2006), and Ingledew et al. (2009).

4. Importance of coproducts

DDGS from most modern U.S. fuel ethanol plants typically contains about 30% protein, 10% fat, at least 40% neutral detergent fiber, and up to 12% starch (Rosentrater and Muthukumarappan, 2006). Composition, however, can vary between plants and even within a single plant over time, due to a number of factors. For example, Table 1 summarizes composition of DDGS samples collected from five ethanol plants in South Dakota. On a dry basis, crude protein levels ranged from 28.3 to 31.8%; crude lipid varied between 9.4 and 11.0%; ash ranged from 4.1 to 13.3%. In terms of within-plant variability, the crude protein, crude lipid, and starch content all exhibited relatively low variation, whereas neutral detergent fiber (NDF), acid detergent fiber (ADF), and ash all had substantially higher variability.

Plant	Protein	Lipid	NDF	ADF	Starch	Ash
1	28.33^{b} (1.25)	10.76^{a} (1.00)	31.84^{b} (4.02)	15.56^{a} (2.29)	11.82^{a} (1.20)	13.27^{a} (3.10)
2	30.65^{a} (1.20)	9.75^{a} (1.05)	39.90^{a} (3.95)	15.21^{a} (3.95)	9.81^{a} (1.52)	12.84^{a} (2.56)
3	28.70^{a} (1.32)	10.98^{a} (0.95)	38.46^{a} (4.01)	17.89^{a} (4.01)	11.59^{a} (1.42)	11.52^{a} (3.05)
4	30.65^{a} (1.23)	9.40^{b} (0.16)	36.73^{a} (1.07)	15.28^{a} (0.49)	9.05^{b} (0.33)	4.13^{b} (0.21)
5	31.78^{a} (0.63)	9.50^{b} (0.41)	38.88^{a} (0.86)	17.24^{a} (1.12)	10.05^{a} (0.65)	4.48^{b} (0.22)

Table 1. Composition (% db) of DDGS from five ethanol plants in South Dakota (± 1 standard deviation in parentheses). Statistically significant differences among plants for a given nutrient are denoted by differing letters, α=0.05, LSD (adapted from Bhadra et al., 2009).

Furthermore, DDGS from 49 plants from 12 states were analyzed for proximate composition (Table 2) and amino acid profiles (Table 3) (UMN, 2011). Dry matter content varied from 86.2% to 92.4%, while protein varied from 27.3% to 33%. Crude fat content displayed even higher variability, and ranged from 3.5% to 13.5%; crude fiber ranged from 5.37% to 10.58%; and ash content varied from 2.97% to 9.84%. On average, geographic trends were not readily apparent for any of the nutrient components. In terms of amino acids, lysine ranged from 0.61% to 1.19%, but again, no geographic trends were apparent.

Some plants are beginning to implement various fractionation processes (either pre-fermentation or post-fermentation) in order to produce multiple product streams (RFA, 2009a). These new processes can lead to additional differences in DDGS nutrient levels. For example, various techniques for dry fractionation and wet fractionation have been developed to concentrate protein, fiber, and oil components from the endosperm (which contains the starch). This allows a highly-concentrated starch substrate to be introduced to the fermentation process, and it allows the other components to be used for human food applications. Singh and Johnston (2009) have provided an extensive discussion regarding various pre-fermentation fractionation approaches. On the other hand, post-fermentation fractionation techniques have also been examined. For example, Srinivasan et al. (2005) used a combination of (air classification and sieving to separate fiber particles from DDGS. Processes have also been developed to remove corn oil from thin stillage and CDS; although the resulting corn oil fractions cannot be used as food-grade oil, they can readily be converted into biodiesel. All of these approaches, if implemented commercially, will alter the composition of the resulting DDGS.

State	Plants Sampled	Dry Matter (%)	Crude Protein (%)	Crude Fat (%)	Crude Fiber (%)	Ash (%)
Minnesota	12	89.03	30.70	11.73	6.96	6.63
Illinois	6	89.72	29.98	11.48	7.26	5.60
Indiana	2	90.55	29.40	12.80	8.07	5.86
Iowa	7	88.92	31.23	10.27	7.57	5.76
Kentucky	3	90.57	29.43	9.77	9.28	4.47
Michigan	1	89.60	32.60	11.00	7.37	6.06
Missouri	2	87.90	30.45	10.25	7.17	5.39
Nebraska	4	89.02	30.40	11.35	8.13	4.23
New York	1	88.21	30.00	9.60	7.87	4.55
North Dakota	4	89.21	31.75	11.70	6.89	6.32
South Dakota	4	88.61	31.80	11.53	6.65	4.78
Wisconsin	3	89.68	31.70	11.63	7.59	5.77
Overall Average	49 (Total)	89.25	30.79	11.09	7.57	5.45

Table 2. Composition (% db) of DDGS samples from 49 ethanol plants from 12 states (adapted from UMN, 2011).

State	Plants Sampled	Agrinine (%)	Histidine (%)	Isoleucine (%)	Leucine (%)	Lysine (%)	Methionine (%)
Minnesota	12	1.39	0.84	1.20	3.63	0.99	0.61
Illinois	6	1.37	0.82	1.15	3.45	0.94	0.63
Indiana	2	1.19	0.79	1.08	3.28	0.85	0.60
Iowa	7	1.34	0.86	1.20	3.63	0.95	0.61
Kentucky	3	1.35	0.79	1.09	3.33	0.89	0.66
Michigan	1	1.28	0.86	1.18	3.67	0.87	0.71
Missouri	2	1.35	0.83	1.18	3.68	0.89	0.73
Nebraska	4	1.46	0.88	1.18	3.61	1.05	0.65
New York	1	1.46	0.85	1.21	3.64	1.04	0.61
North Dakota	4	1.37	0.88	1.24	3.76	0.97	0.65
South Dakota	4	1.47	0.87	1.22	3.70	1.08	0.62
Wisconsin	3	1.45	0.86	1.24	3.75	1.07	0.59
Overall Average	49	1.37	0.84	1.18	3.59	0.96	0.64

State	Plants Sampled	Phenylalanine (%)	Threonine (%)	Tryptophan (%)	Valine (%)	Tyrosine (%)
Minnesota	12	1.59	1.17	0.24	1.62	1.20
Illinois	6	1.51	1.11	0.22	1.52	1.22
Indiana	2	1.45	1.04	0.21	1.44	-
Iowa	7	1.57	1.14	0.25	1.60	-
Kentucky	3	1.48	1.09	0.26	1.43	-
Michigan	1	1.52	1.15	0.25	1.57	-
Missouri	2	1.53	1.15	0.24	1.58	-
Nebraska	4	1.58	1.15	0.26	1.58	1.14
New York	1	1.63	1.11	0.20	1.59	1.19
North Dakota	4	1.62	1.19	0.25	1.67	-
South Dakota	4	1.67	1.19	0.23	1.63	1.35
Wisconsin	3	1.65	1.14	0.22	1.64	1.25
Overall Average	49	1.56	1.13	0.24	1.57	1.22

Table 3. Amino acid profiles (% db) of DDGS samples from 49 ethanol plants from 12 states (adapted from UMN, 2011).

The U.S. ethanol industry's primary market for distillers grains has historically been as a commodity livestock feed. Most often this has been in the form of DDGS, and to a lesser degree in the form of DWG; the other coproducts are sold in much lower quantities than either DDGS or DWG and some are not always produced either). Feeding ethanol coproducts to animals is a practical method of utilizing these materials because they contain high nutrient levels, and they are digestible (to varying degrees) by most livestock. And, use of DDGS in animal feeds (instead of corn grain) helps to offset the corn which has been redirected to ethanol production. Over 80% of all distillers grains is used in beef and dairy diets; due to their ability to utilize high levels of fiber, ruminant animals have become the dominant consumers of DDGS. But, as livestock producers and animal nutritionists increase their knowledge, through research and experience, the swine and poultry markets are also increasing their consumption as well (UMN, 2011). Over the years, numerous research studies have been conducted on coproduct use in livestock diets, for both ruminant and monogastric feeds. Table 4 lists some of this research. Depending on the diet composition used, all livestock species have been shown to thrive at 10% DDGS inclusion, and most can tolerate levels up to 20% (or even more).

Species	Citation	Species	Citation
Beef		Dairy	
	Loy et al., 2007		Kleinschmit et al., 2007
	MacDonald et al., 2007		Anderson et al., 2006
	Martin et al., 2007		Kleinschmit et al., 2006
	Roeber et al., 2005		Leonardi et al., 2005
	Al-Suwaiegh et al., 2002		Birkelo et al., 2004
	Peter et al., 2000		McKendrick et al., 2003
	Lodge et al., 1997a		Al-Suwaiegh et al., 2002
	Lodge et al., 1997b		Liu et al., 2000
	Fron et al., 1996		Huang et al., 1999
	Klopfenstein, 1996		Schingoethe et al., 1999
	Ham et al., 1994		Batajoo and Shaver, 1998
	Larson et al., 1993		Nichols et al., 1998
	Donaldson et al., 1991		Clark and Armentano, 1997
	McCann et al., 1991		DePeters et al., 1997
			O'Mara et al., 1997
			Zhu et al., 1997
			Arosemena et al., 1995
			Murphy et al., 1995
			Powers et al., 1995
			Ham et al., 1994
			Clark and Armentano, 1993
Swine		Poultry	
	Stein and Shurson, 2009		Waldroup et al., 2007
	Pedersen et al., 2007		Wang et al., 2007a
	Widmer et al., 2007		Wang et al., 2007b
	Fastinger et al., 2007		Wang et al., 2007c
	Stein et al., 2006		Batal and Dale, 2006
	Whitney et al., 2006a		Fastinger et al., 2006
	Whitney et al., 2006b		Martinez-Amezcua et al., 2006
	Whitney et al., 2006c		Noll, 2006
	Whitney et al., 2006d		Lumpkins and Batal, 2005
	Nyachoti et al., 2005		Lumpkins et al., 2005
	Whitney and Shurson, 2004		Roberson et al., 2005
	Gralapp et al., 2002		Biggs et al., 2004
	Spiehs et al., 2002		Lumpkins et al., 2004
	Nicolai et al., 1999		Martinez Amezcua et al., 2004
	Cromwell et al., 1993		Batal and Dale, 2003
			Roberson, 2003
			Cromwell et al., 1993

Table 4. Summary of livestock research on fuel ethanol coproducts.

DDGS use in livestock diets has continued to increase over the years. Predictions of peak potential for DDGS use in domestic U.S. beef, dairy, swine, and poultry markets have estimated that between 40 and 60 million t could be used in the U.S. each year, depending upon inclusion rates for each species (Staff, 2005; Cooper, 2006; U.S. Grains Council, 2007). Globally, the need for protein-based animal feeds continues to grow. Of the 23 million t of DDGS produced in 2008 (RFA, 2009b), 4.5 million t were exported to international markets (FAS, 2009); this accounted for nearly 20% of the U.S. DDGS production that year (Figure 6). And the potential for global exports is projected to increase for the foreseeable future (U.S. Grains Council, 2007).

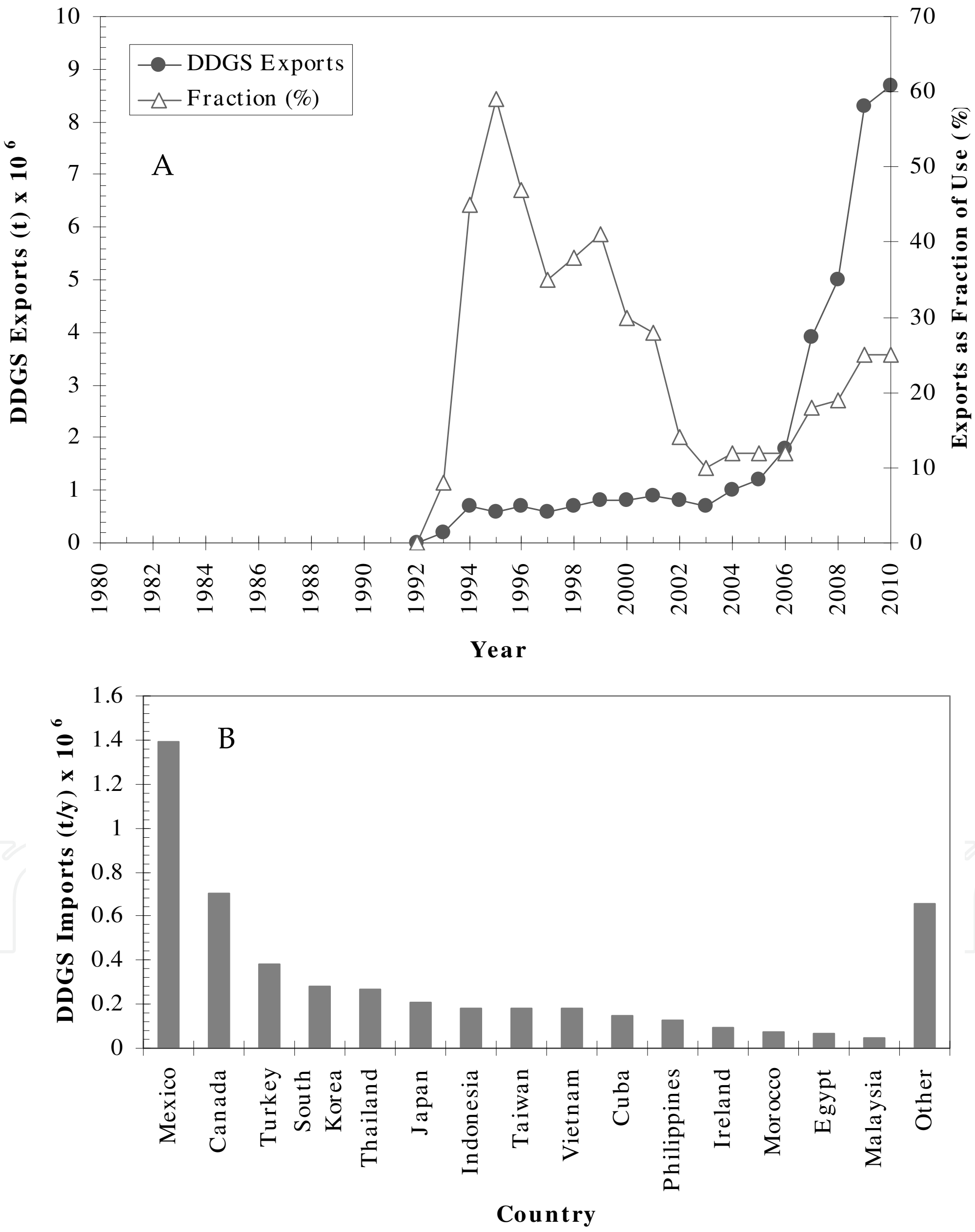

Fig. 6. A. U.S. DDGS exports in 2008. B. Countries who imported DDGS in 2008 (adapted from Hoffman and Baker, 2010).

Not only are coproducts important to the livestock industry as feed ingredients, but they are also essential to the sustainability of the fuel ethanol industry itself. In fact, the sale of distillers grains (all types – dry and wet) contributes substantially to the economic viability of each ethanol plant (sales can generally contribute between 10 and 20% of a plant's total revenue stream (Figure 7), but at times it can be as high as 40%), depending upon the market conditions for corn, ethanol, and distillers grains. This is the reason why these process residues are referred to as "coproducts", instead of "byproducts" or "waste products"; they truly are products in their own right along with the fuel.

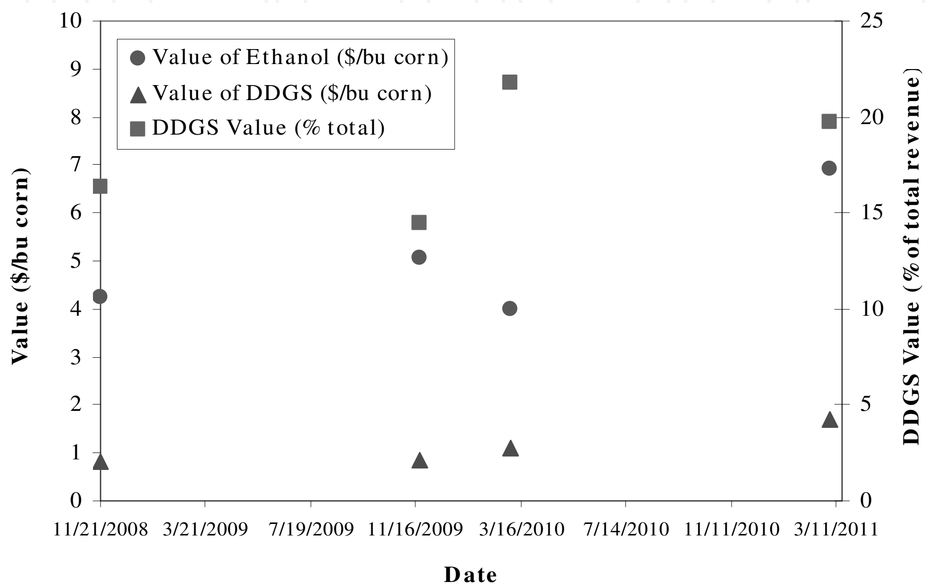

Fig. 7. Some relative comparisons of the value of DDGS and fuel ethanol to ethanol plant profits (adapted from DTN, 2011).

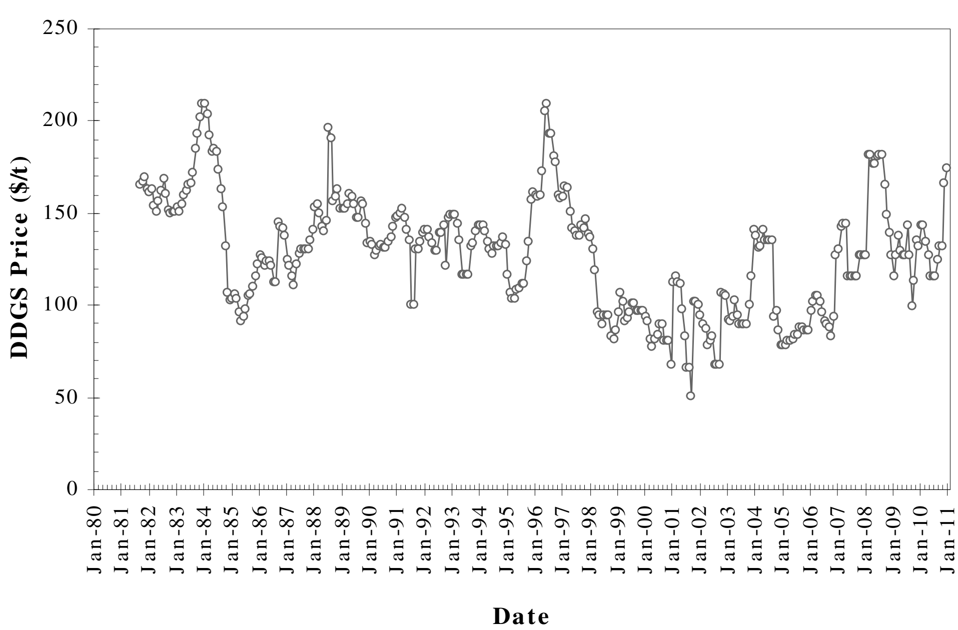

Fig. 8. DDGS sales price over time (monthly averages) (adapted from ERS, 2011).

So the sales price of DDGS is important to ethanol manufacturers and livestock producers alike. Over the last three decades, the price for DDGS has ranged from approximately \$50.71/t up to \$209.44/t (Figure 8). DDGS and corn prices have historically paralleled each other very closely (Figure 9). This relationship has been quite strong over the last several

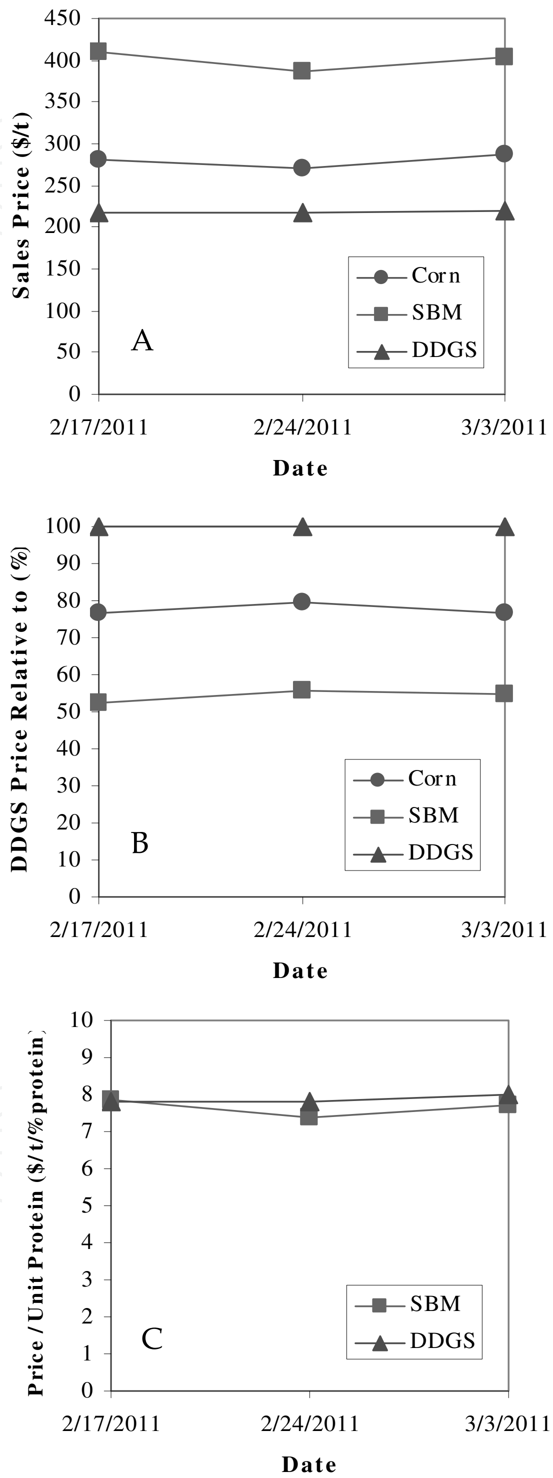

Fig. 9. A. Some comparisons of DDGS, soybean meal (SBM), and corn sales prices. B. Relative price comparisons. C. Cost comparisons on a per unit protein basis (adapted from DTN, 2011).

years. This is not surprising, as DDGS is most often used to replace corn in livestock diet formulations. DDGS has increasingly been used as a replacement for soybean meal as well, primarily as a source of protein. Even so, DDGS has historically been sold at a discounted price vis-à-vis both corn and soybean meal. This has been true on a volumetric unit basis, as well as per unit protein basis (Figure 9).

5. Coproduct evolution

The ethanol industry is dynamic and has been evolving over the years in order to overcome various challenges associated with both fuel and coproduct processing and use (Rosentrater, 2007). A modern dry grind ethanol plant is considerably different from the inefficient, input-intensive Gasohol plants of the 1970s. New developments and technological innovations, to name but a few, include more effective enzymes, higher starch conversions, better fermentations, cold cook technologies, improved drying systems, decreased energy consumption throughout the plant, increased water efficiency and recycling, and decreased emissions. Energy and mass balances are becoming more efficient over time. Many of these improvements can be attributed to the design and operation of the equipment used in modern ethanol plants. A large part is also due to computer-based instrumentation and control systems.

Many formal and informal studies have been devoted to adjusting existing processes in order to improve and optimize the quality of the coproducts which are produced. Ethanol companies have recognized the need to produce more consistent, higher quality DDGS which will better serve the needs of livestock producers. The sale of DDGS and the other coproducts has been one key to the industry's success so far, and will continue to be important to the long-term sustainability of the industry. Although the majority of DDGS is currently consumed by beef and dairy cattle, use in monogastric diets, especially swine and poultry, continues to increase. And use in non-traditional species, such as fish, horses, and pets has been increasing as well.

Additionally, there has been considerable interest in developing improved mechanisms for delivering and feeding DDGS to livestock vis-à-vis pelleting/densification (Figure 10). This is a processing operation that could result in significantly better storage and handling characteristics of the DDGS, and it would drastically lower the cost of rail transportation and logistics (due to increased bulk density and better flowability) (Figure 11). Pelleting could also broaden the use of DDGS domestically (e.g., improved ability to use DDGS for rangeland beef cattle feeding and dairy cattle feeding) as well as globally (e.g., increased bulk density would result in considerable freight savings in bulk vessels and containers).

There are also many new developments underway in terms of evolving coproducts. These will ultimately result in more value streams from the corn kernel (i.e., upstream fractionation) as well as the resulting distillers grains (i.e., downstream fractionation) (Figure 12). Effective fractionation can result in the separation of high-, mid-, and low-value components. Many plants have begun adding capabilities to concentrate nutrient streams such as oil, protein, and fiber into specific fractions, which can then be used for targeted markets and specific uses. These new processes are resulting in new types of distillers grains (Figure 13).

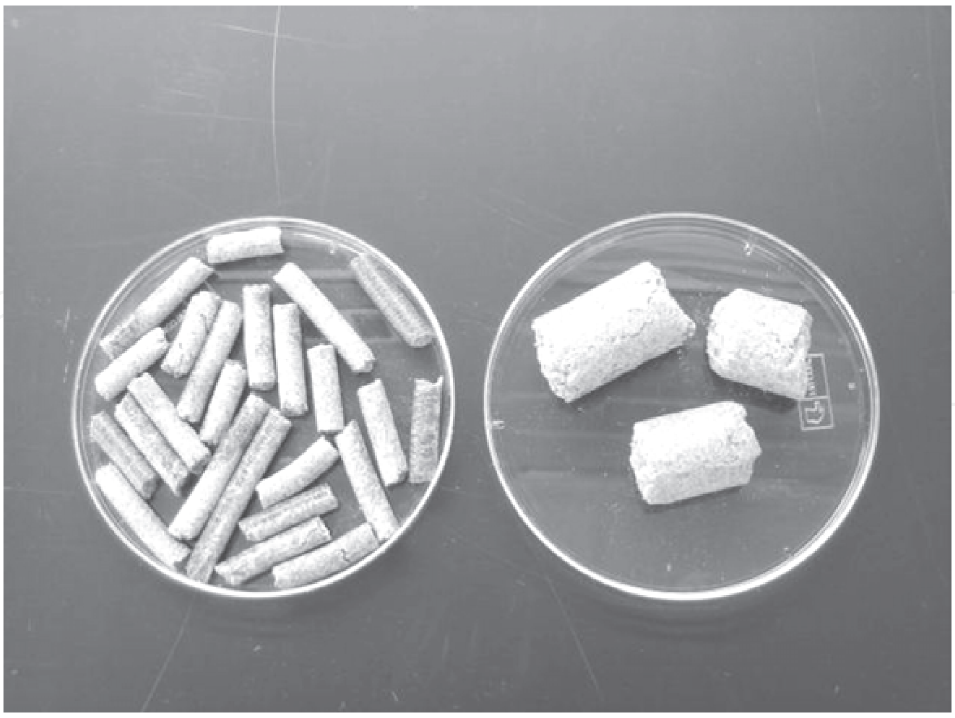

Fig. 10. Pelleting is a unit operation that can improve the utility of DDGS, because it improves storage and handling characteristics, and allows more effective use in dairy cattle feeding and range land settings for beef cattle.

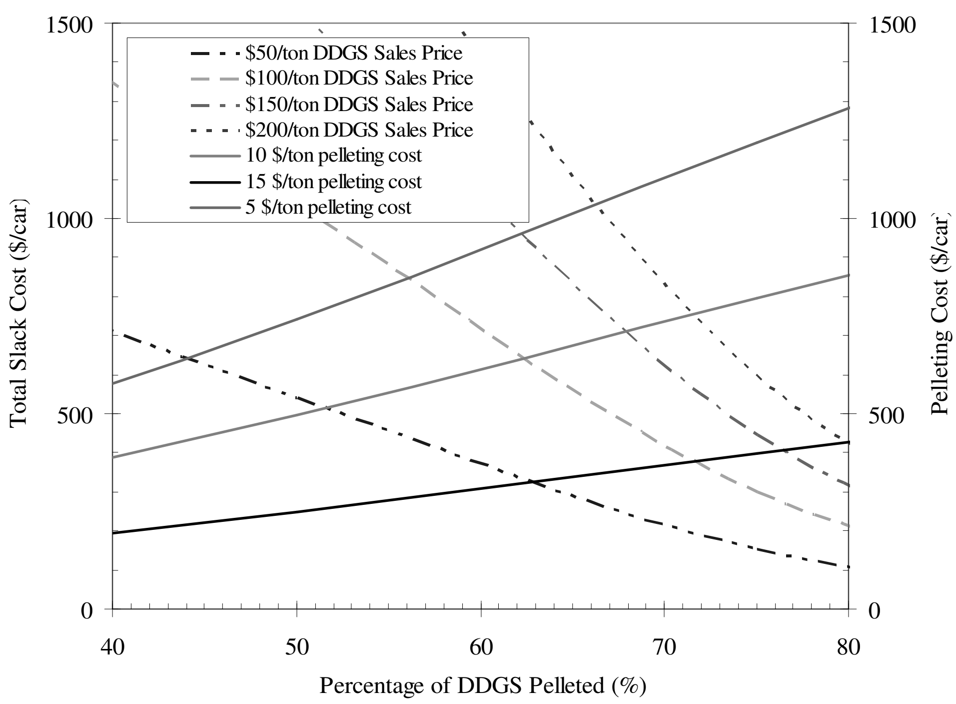

Fig. 11. By pelleting, empty space in rail cars is minimized during shipping. Techno-economic analysis of the resulting slack (i.e., wasted space) costs and costs of pelleting for each rail car due to differing DDGS sales prices and pelleting costs indicates the proportion of DDGS which needs to be pelleted in order to achieve breakeven for this process (adapted from Rosentrater and Kongar, 2009).

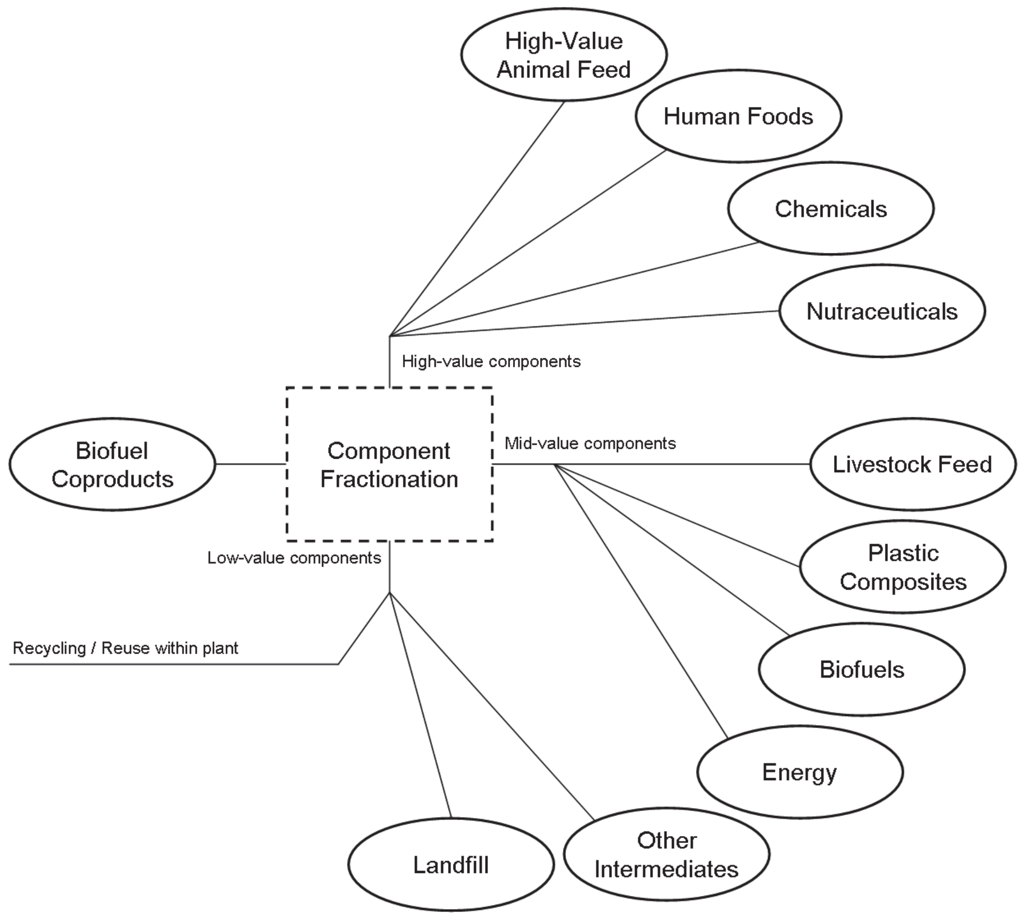

Fig. 12. Fractionation of DDGS into high-, mid-, and low-value components offers the opportunity for new value streams.

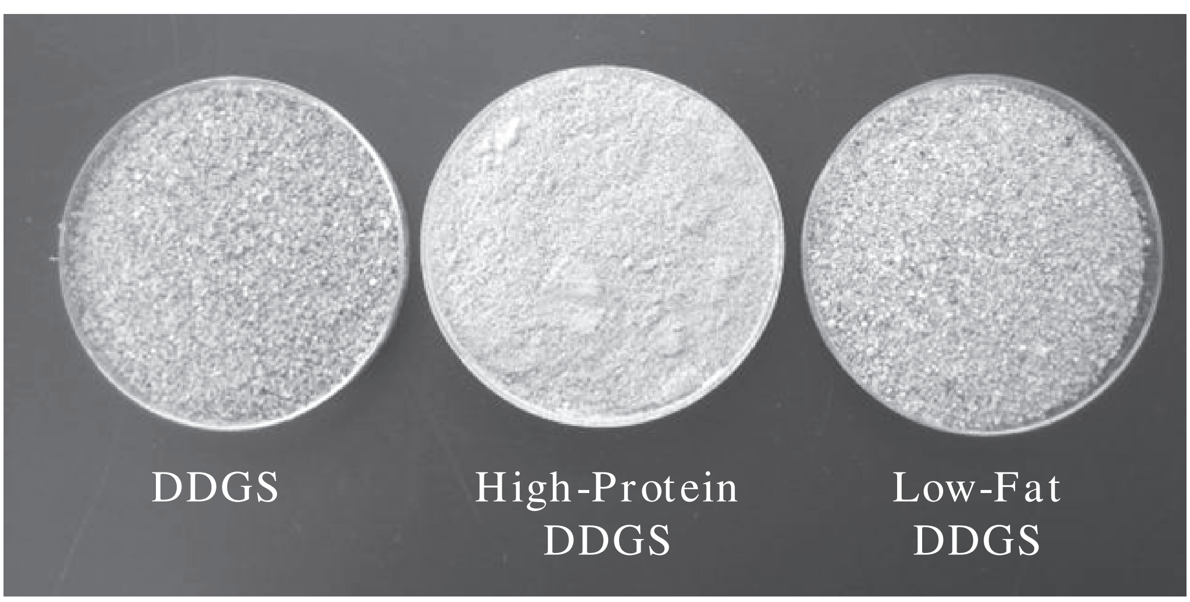

Fig. 13. Examples of traditional, unmodified DDGS and some fractionated products (e.g., high-protein and low-fat DDGS) which are becoming commercially available in the marketplace.

For example, if the lipids are removed from the DDGS (Figure 14), they can readily be converted into biodiesel, although they cannot be used for food grade corn oil, because they are too degraded structurally. Another example is concentrated proteins, which can be used for high-value animal feeds (such as aquaculture or pet foods), or other feed applications which require high protein levels. Additionally, DDGS proteins can be used in human foods (Figure 15). Furthermore, other components, such as amino acids, organic acids, or even nutraceutical compounds (such as phytosterols and tycopherols) can be harvested and used in high-value applications.

Mid-value components, such as fiber, can be used as biofillers for plastic composites (Figure 16), as feedstocks for the production of bioenergy (e.g., heat and electricity at the ethanol plant via thermochemical conversion) (Figure 17), or, after pretreatment to break down the lignocellulosic structures, as substrates for the further production of ethanol or other biofuels.

In terms of potential uses for the low-value components, hopefully mechanisms will be developed to alter their structures and render them useful, so that they will not have to be landfilled. Fertilizers are necessary in order to sustainably maintain the flow of corn grain into the ethanol plant, so land application may be an appropriate venue for the low value components.

As these process modifications are developed, validated, and commercially implemented, improvements in the generated coproducts will be realized and unique materials will be produced. Of course, these new products will require extensive investigation in order to determine how to optimally use them and to quantify their value propositions in the marketplace.

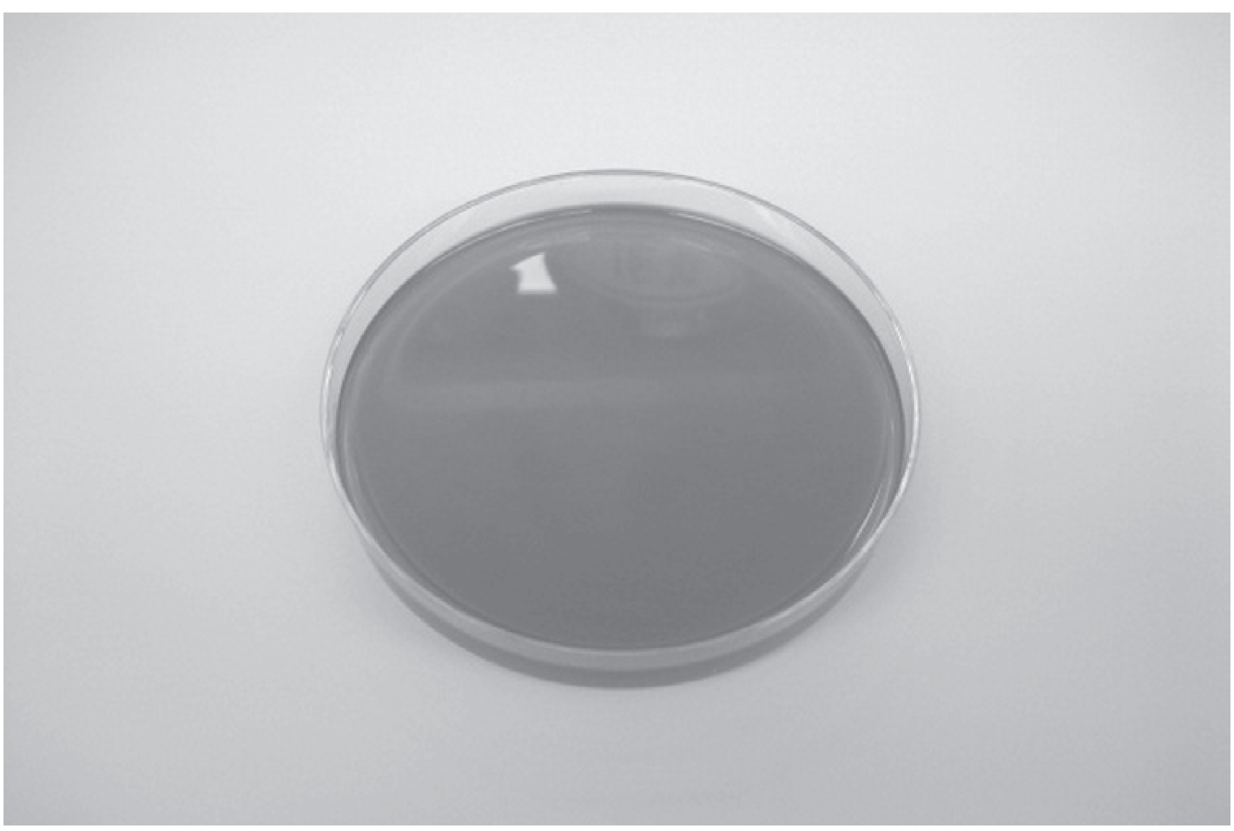

Fig. 14. Corn oil which has been extracted from DDGS can be used to manufacture biodiesel.

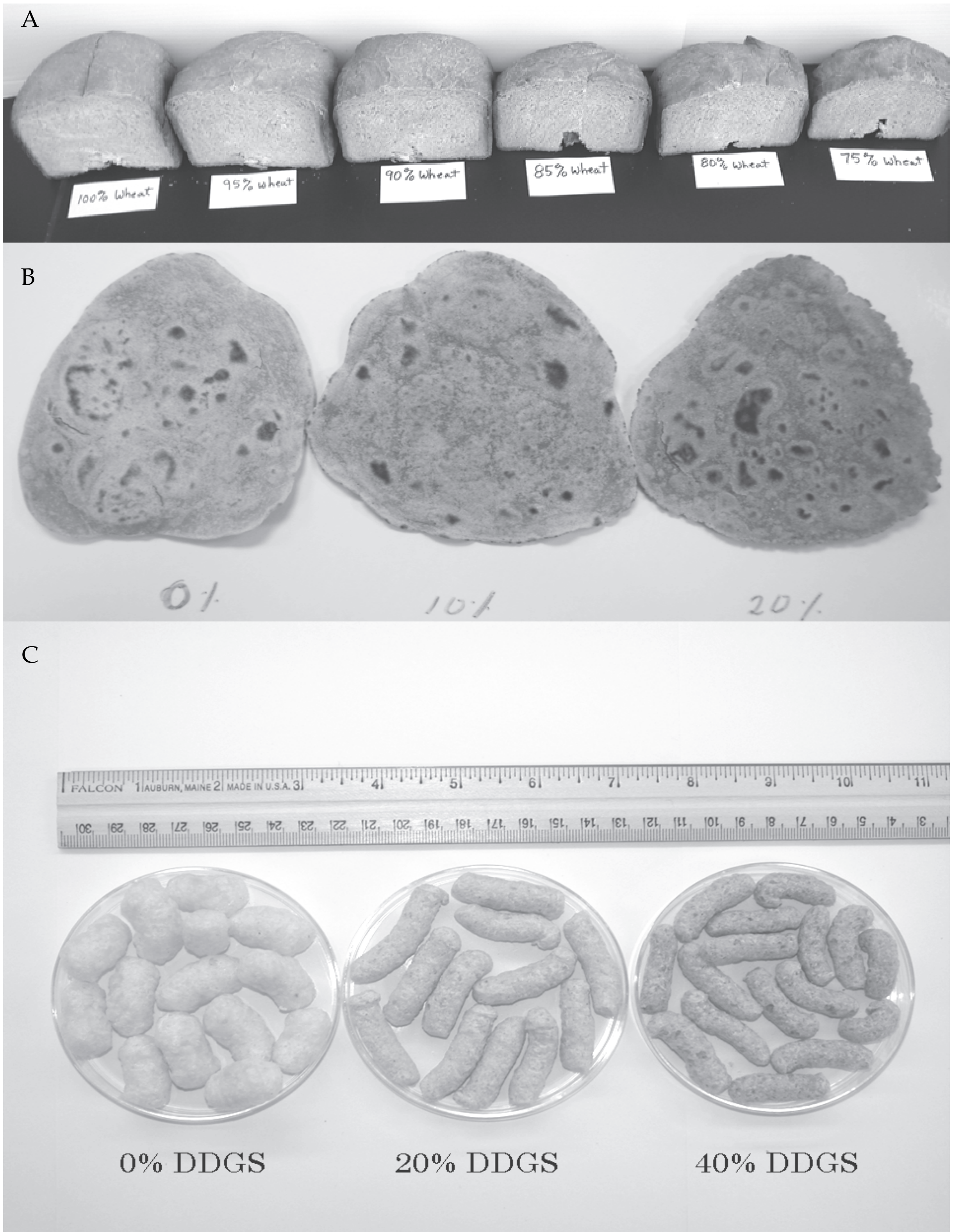

Fig. 15. As a partial substitute for flour, high-value DDGS protein can be used to improve the nutrition of various baked foods such as (A) bread, (B) flat bread, and (C) snack foods, by increasing protein levels and decreasing starch content.

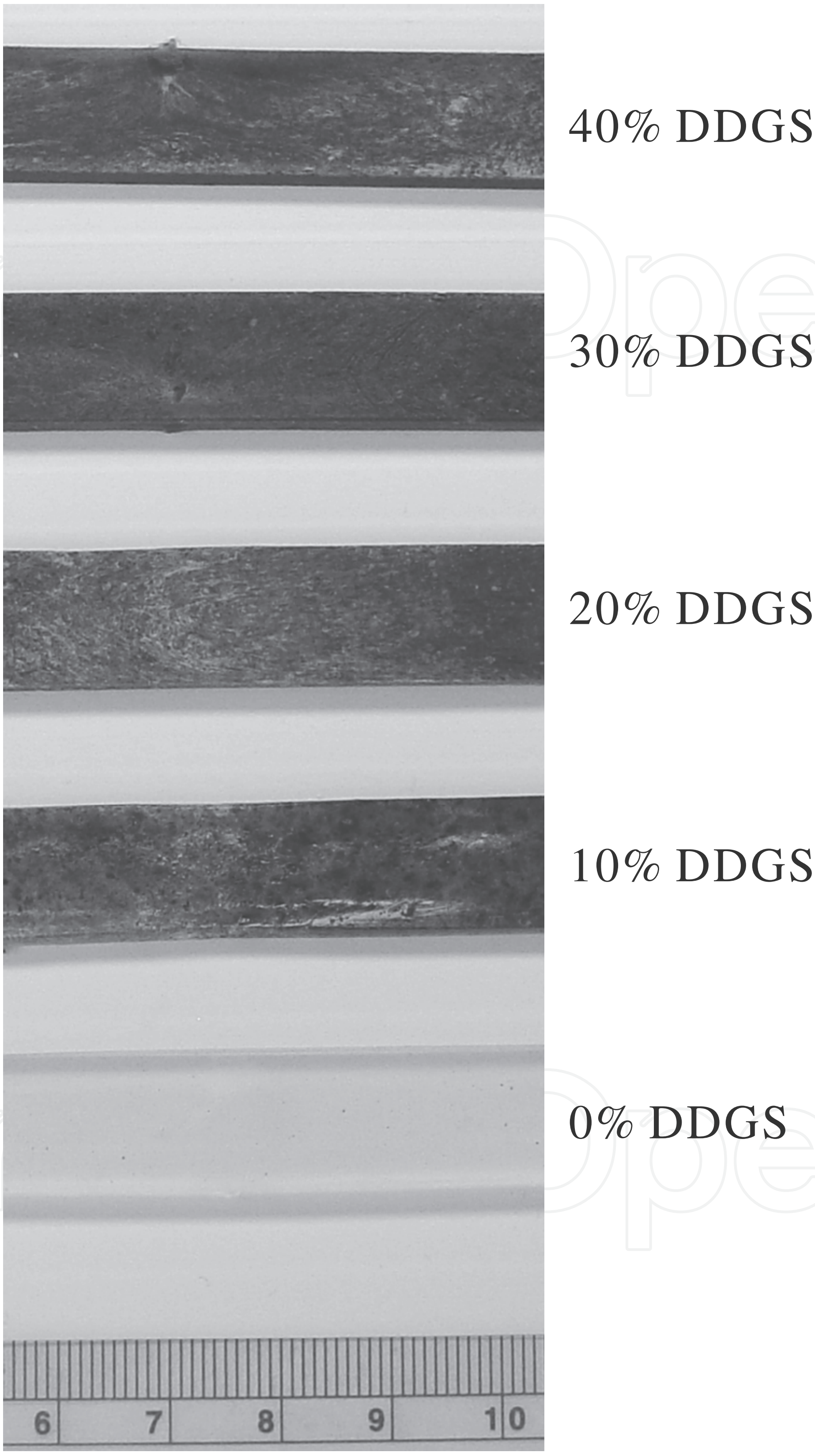

Fig. 16. Mid-value or low-value fractions from DDGS (such as fiber) have been shown to be an effective filler in plastics, replacing petroleum additives and increasing biodegradability. Scale bar indicates mm.

Fig. 17. Mid-value or low-value fractions from DDGS (such as fiber) can be thermochemically converted into biochar, which can subsequently be used to produce energy, fertilizer, or as a precursor to other bio-based materials.

6. Conclusion

The fuel ethanol industry has been rapidly expanding in recent years in response to government mandates, but also due to increased demand for alternative fuels. This has become especially true as the price of gasoline has escalated and fluctuated so drastically, and the consumer has begun to perceive fuel prices as problematic. Corn-based ethanol is not the entire solution to our transportation fuel needs. But it is clearly a key component to the overall goal of energy independence. Corn ethanol will continue to play a leading role in the emerging bioeconomy, as it has proven the effectiveness of industrial-scale biotechnology and bioprocessing for the production of fuel. And it has set the stage for advanced biorefineries and manufacturing techniques that will produce the next several generations of advanced biofuels. As the biofuel industry continues to evolve, coproduct materials (which ultimately may take a variety of forms, from a variety of biomass substrates) will remain a cornerstone to resource and economic sustainability. A promising mechanism to achieve sustainability will entail integrated systems (Figure 18), where material and energy streams cycle and recycle (i.e., upstream outputs become downstream inputs) between various components of a biorefinery, animal feeding operation, energy (i.e., heat, electricity, steam, etc.) production system, feedstock production system, and other systems. By integrating these various components, a diversified portfolio will not only produce fuel, but also fertilizer, feed, food, industrial products, energy, and most importantly, will be self-sustaining.

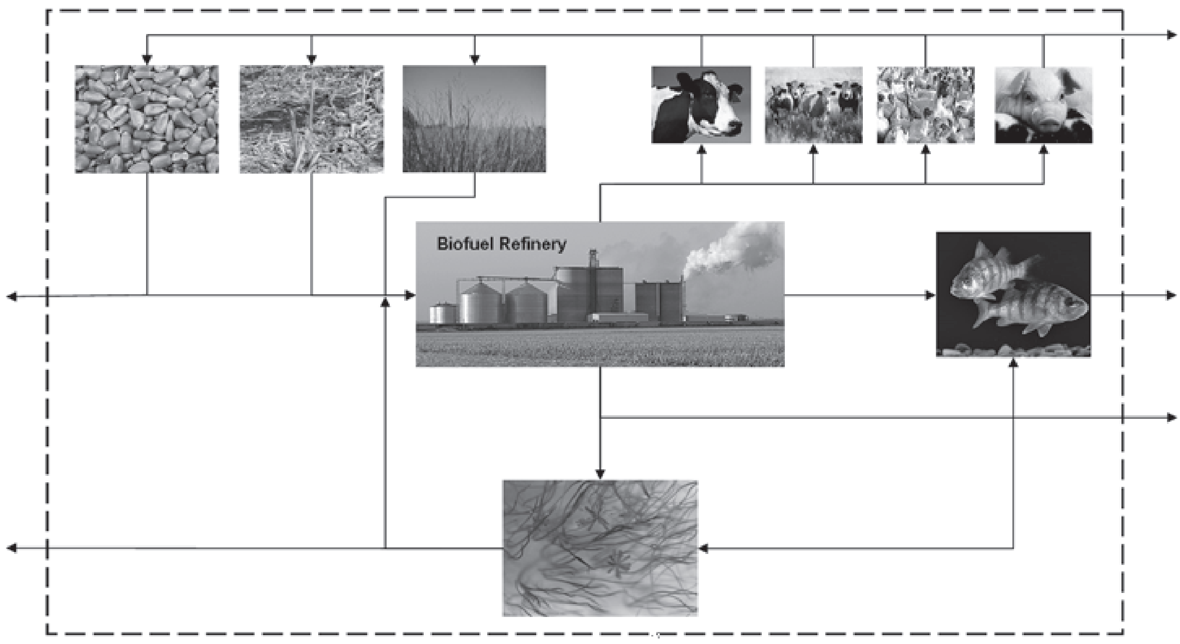

Fig. 18. Coproducts such as DDGS will continue to play a key role as the biofuel industry evolves and becomes more fully integrated. This figure illustrates one such concept.

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Biofuel's Engineering Process Technology

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This book aspires to be a comprehensive summary of current biofuels issues and thereby contribute to the understanding of this important topic. Readers will find themes including biofuels development efforts, their implications for the food industry, current and future biofuels crops, the successful Brazilian ethanol program, insights of the first, second, third and fourth biofuel generations, advanced biofuel production techniques, related waste treatment, emissions and environmental impacts, water consumption, produced allergens and toxins. Additionally, the biofuel policy discussion is expected to be continuing in the foreseeable future and the reading of the biofuels features dealt with in this book, are recommended for anyone interested in understanding this diverse and developing theme.