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CEDAR RAPIDS FOOD AND BIOPROCESSORS MANUFACTURING REPORT

2018

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Executive Summary

Cedar Rapids, Iowa, has a long and notable history as a center of bioprocessing activity in the United States. Consequently, many market leaders have selected Cedar Rapids as a prime location in which to operate. The City of Cedar Rapids and Iowa State University (ISU) have established a partnership in efforts to understand and support further development of the bioprocessing and manufacturing industry in Cedar Rapids. ISU is a world leader in education and research for agriculture, bioprocessing, and engineering. Therefore, this unique public-private partnership combines excellence across industry, higher education, and the public sector to create a framework to sustain unparalleled competitive advantage for bioprocessing companies in Cedar Rapids.

This work provides a foundational overview of the current practices of major bioprocessing activities in Cedar Rapids. Namely, corn, oats, and soybeans processing; yeast and fermentation products manufacturing; and processed food manufacturing. The value of corn and oats raw materials processed in Cedar Rapids exceeds $1.1 billion. For each job created in the food manufacturing and bioprocessing industry serving Cedar Rapids, four additional jobs are supported throughout the wider economy. Currently, the bioprocessing industry in Cedar Rapids employs approximately 5,000 individuals in manufacturing activities, and median income for cluster employment is 38% higher than the citywide average. For the period between 2007 and 2016, employment in the food and bioprocessing cluster increased at a rate more than double that found in other sectors, and it’s notable this increase occurred as total manufacturing employment decreased in the regional economy. In the past 10 years, the value of goods and services produced by the food and bioprocessing cluster increased at a rate 1.5 times greater than general economic growth in the City of Cedar Rapids.

Included in this report are details of the major process steps of each bioprocessing activity, descriptions of the major products and byproducts, and discussions of water, energy use, and waste generation from each area. Product volumes, economic trends, and current market values are included when available. Historical economic data for major products is included in the appendix.

Areas for potential growth in the current processing and manufacturing practices of the major bioprocessing activities are identified through evaluation of current scientific literature and survey feedback from some of the major plants and facilities in Cedar Rapids. These areas will be explored in depth in future technical publications in efforts to offer specific means to grow and improve current practices.

Table of Contents

1. List of Terms

Amylopectin
Highly branched polysaccharide composed of glucose units with linearly connected α(1-4) bonds and branched α(1-6) bonds occurring approximately every 24–30 glucose units. Branching allows fast enzymatic degradation.

Amylose
Linear helical polysaccharide composed of α-D-glucose units bonded through α(1-4) glycosidic linkages.

Degree of depolymerization (DP)
Number of monomeric units in a macromolecule or polymer.

Dextrose
Fully hydrolyzed or depolymerized form of starch. Also known as glucose.

Dextrose equivalent (DE)
Measure of the amount of reducing sugars determined by heating a syrup in a reducing solution of copper sulfate. The DE gives an indication of the degree of polymerization of starch sugars.

Distillers dried grains with solubles (DDGS)
Nutrient rich coproduct of dry-grind ethanol production. Used as a feed ingredient for energy and protein supplementation.

Endosperm
Part of the seed that acts as food storage for the developing embryo (germ). Contains starch, protein, and other nutrients.

Fructose
Monosaccharide isomer of glucose. Used in a variety of proportions with glucose to produce different corn syrups.

Germ
Reproductive portion of seed that germinates to grow into a plant. Seed embryo.

Hexane
Organic solvent used to extract oil from corn and soybeans.

High fructose corn syrup (HFCS)
Sweetener made from corn starch that is produced from glucose using an enzyme called glucose isomerase.

Hominy
Coarsely ground corn used to make grits. Also used as animal feed.

Hydroclone
Device that applies centrifugal force to a flowing liquid mixture that separates heavy and light components.

Lactic acid
Organic compound produced by the bacteria *Lactobacillus* during the steeping of corn as part of the first processing step in a corn wet milling facility. Assists in the softening of the corn kernel during steeping.

Lecithin
Mixture of phosphatides (phospholipids) derived from vegetables. Lecithin has a variety of purposes including acting as a wetting and dispersing agent, emulsifier, stabilizer, and viscosity reducer.

Maltodextrin
Polysaccharide composed of D-glucose units that are primarily linked with α(1-4) glycosidic bonds. Used as a food additive commonly in the production of soft drinks and candy.

Pericarp
Outermost layer of seed or fruit.

Triglyceride (triacylglycerol)
Ester made from three fatty acid and a glycerol. Main constituents of fat in animals and plants.

USDA ERS
United States Department of Agriculture Economic Research Service. Federal statistical agency covered by the Office of Management and Budget's (OMB) Statistical Policy directives. ERS research and analysis covers topics including agricultural economy, food and nutrition, food safety, global markets and trade, resources and environment, and rural economy.

Wet distillers grains (WDG)
Also termed *distillers wet grains* or DWG. Unfermented grain residues produced in the dry-grind ethanol process that have not been dried.

Zein
Principle class of protein found in corn (maize).

2. Introduction

Cedar Rapids, Iowa, was founded in 1838 on the banks of the Cedar River. The city prospered using the rapids of the Cedar River for milling, which led to grain production, food processing, and meatpacking industries developing throughout the 20th century. Cedar Rapids is currently one of the leading bioprocessing and food ingredient manufacturing centers in North America. Major international agricultural and food processing companies have plants in Cedar Rapids, such as Quaker Oats, General Mills, Archer Daniels Midland, Ingredion, Dupont Industrial Biosciences, and Cargill. Cedar Rapids has a population of approximately 150,000 residents. Nearly 18% of employed individuals in Cedar Rapids work in areas of manufacturing and agriculture.[1] The primary grain and seed processing operations in Cedar Rapids are corn, oats, and soybean. Other major bioprocessing and manufacturing operations include yeast and fermentation products and processed foods.

The food and bioprocessing and manufacturing cluster in Cedar Rapids has sustained robust growth in employment, wages, value, and production over the past decade. While the manufacturing sector in Cedar Rapids experienced a decrease of 1% in employment from 2007 to 2016, the food and bioprocessing cluster employment increased by 1.2%.[2] Average annual wages in Cedar Rapids over the same period was $50,911, while the food and bioprocessing cluster average annual wages was $70,384.[2] Earnings for firms per job in the food and bioprocessing cluster was $89,387, while the average was $61,281.[3] Growth of the nominal gross domestic product of the manufacturing sector in Cedar Rapids was 2.2% as compared to that of the food and bioprocessing cluster which was 4.5%.[4] These statistics support the notion that the food and bioprocessing cluster in Cedar Rapids is well positioned for continued growth. With the help of innovative technologies and new companies entering the sector, food and bioprocessing activities in Cedar Rapids will support continued and even greater growth and success for the city and region.

The purpose of this report is to provide a review and background of the feedstocks, technologies, and processes associated with the bioprocessing industry in Cedar Rapids. It is envisioned that from this foundational report will stem a series of technical reports evaluating specific areas that have potential for technological advances, improvements in water, energy and waste utilization, coproduct valorization, or process intensification. The technical reports will be written by individuals at Iowa State University who may provide technical expertise and lab-scale research to support the development of these areas. Ultimately, the scope of this project aims to serve the growth and development of the bioprocessing industry in Cedar Rapids as well as related businesses and industries across the State of Iowa.

Additionally, from an economic development perspective, the ISU–Cedar Rapids partnership is a unique public-private initiative. As an important part of the overall effort, the waste stream report helps to enhance the initiative’s framework for successful implementation of technology, innovation, and industry cluster based economic development strategies. For industry partners, the net effect of all partnership activities will be to effectively support maximum competitive advantage from location in Cedar Rapids. Through ongoing collaboration, food and bioprocessing industries in Cedar Rapids gain access to ISU research and faculty expertise delivered through coordination with the local economic development process. Whether stakeholder objectives are connecting university research to industry need, accessing the impact of new and emerging technology, providing technical assistance relating to topics such as waste management and models of industrial organization, serving as a forum for safety or quality issues, and promoting awareness of issues facing industry such as understanding of statewide nutrient reduction, the ISU-Cedar Rapids partnership has a vital role to play. The discussion, planning, and cooperation fostered through this inclusive partnership represent the full scope of action necessary to advance cluster formation across food manufacturing and bioprocessing industries.

A final note on some of the technical content of this report: any masses given in this work in "tons" refer to short tons, that is 2,000 lbs (907 kg). Occasionally the text refers to "metric tons" meaning 1,000 kg (2,205 lbs). The usage of different nomenclature and units is a result of reporting information from a variety of sources, however conversions are made whenever possible to reflect the intended readership's preferred measurement units and vernacular. A bushel of corn is defined to be 56.00 lbs with a moisture content of 15.5%. A bushel of oats is defined to be 32 lbs with 14% moisture. A bushel of soybeans is defined to be 60 lbs with 13% moisture.

3. Cereal Grains and Oilseeds Processed in Cedar Rapids

3.1 CORN

There are five general classes of corn based on kernel characteristics: dent corn, flint corn, popcorn, flour corn, and sweet corn. Most commercial corn is of the dent type, and more specifically, dent corn is used for the dry milling, dry grinding, and wet milling processes discussed in section 4. Corn production in the United States in 2016 totaled 15.1 billion bushels, or 423 million tons.[5] Corn is given a grade number of 1 through 5 by the USDA grading standards outlined in **Table 1**.

A dent corn kernel weighs on average 350 mg, and the general components of a mature kernel are the endosperm (82%), germ (12%), pericarp or hull (5%), and the tip cap (1%).[7, 8] These values are consistent with those given by Watson and reproduced in **Table 3**.[9] There are two types of endosperm in the corn kernel, vitreous and floury. Vitreous endosperm is more compact and translucent. Floury endosperm is opaque and often described as "soft" due to it containing a large number of air spaces.

Endosperm cells contain starch granules that are held together by a protein matrix. The protein matrix in vitreous and floury endosperm is composed of several proteins, the majority of which are albumins, globulins, and glutelins, as well as zein in the case of vitreous endosperm, which are present as protein bodies.[8, 10] Also worth noting is that zein is not one singular protein, but rather is a mixture of different peptides of various molecular size, solubility, and charge. Fractions of zein that have been identified include α-zein, β-zein, γ-zein, C-zein, D-zein, among others.[10]

TABLE 1 – USDA grades and grade requirements for corn*

		Maximum limits of:		
		Damaged kernels		
Grade	Minimum test weight per bushel (lbs)	Heat damaged kernels (%)	Total (%)	Broken corn and foreign material (%)
U.S. No. 1	56	0.1	3	2
U.S. No. 2	54	0.2	5	3
U.S. No. 3	52	0.5	7	4
U.S. No. 4	49	1	10	5
U.S. No. 5	46	3	15	7

U.S. Sample grade is corn that: (a) Does not meet the requirements for the grades U.S. Nos. 1,2,3,4, or 5; or (b) Contains stones with an aggregate weight in excess of 0.1 percent of the sample weight, 2 or more pieces of glass, 3 or more crotalaria seeds (*Crotalaria spp.*), 2 or more castor beans (*Ricinus communis* L.), 4 or more particles of an unknown foreign substance(s) or a commonly recognized harmful or toxic substance(s), 8 or more cockleburs (*Xanthium spp.*), or similar seeds singly or in combination, or animal filth in excess of 0.20 percent in 1,000 grams; or (c) Has a musty, sour, or commercially objectionable foreign odor; or (d) Is heating or otherwise of distinctly low quality.

*Table reproduced from [6]

A depiction of the anatomy of a corn kernel is shown in **Figure 1**. The Corn Refiners Association (CRA) describes the composition of a dent corn kernel to be 70% starch (from the endosperm), 10% protein (gluten), 4% oil (extracted from germ), and 2% fiber (from the hull).[11] A more detailed compositional analysis of yellow dent corn is given in **Table 2**.[9] The unaccounted 14% in the CRA composition may be attributed to the composition being given on a wet basis, or alternatively, it may be due to not listing the minor components as given in Table 2. Considering the starch, protein, and oil (fat) values from the CRA are relatively similar to the values in Table 2 given on a dry basis, it seems reasonable to assume the CRA values are on a dry basis.

As one might expect there is variability in the kernel composition reported by different sources, however, most generally agree within a few percent. Table 3 provides the weight and composition of the component parts of yellow dent corn kernels from seven Midwest hybrids.[9]

TABLE 2 – Yellow dent corn grain (whole kernel)[a]

Characteristic	Dry[b,c] (%)	Wet[b,c] (%)
Moisture	—	16.0
Starch	71.7	60.2
Protein	9.5	8.0
Fat	4.3	3.6
Ash (oxide)	1.4	1.2
Pentosans (as xylose)	6.2	5.2
Fiber (neutral detergent residue)	9.5	8.0
Cellulose + lignin (acid detergent residue)	3.3	2.8
Sugars, total (as glucose)	2.6	2.2
Total carotenoids	0.0026	0.0022

[a] Table recreated from Watson.[9] The values listed represent average compositions.

[b] Moisture, starch, protein, and fat values are averages of dent corn purchased on the open market from 1980–1984 in Illinois, Iowa, and Indiana.

[c] The sum of average characteristic values as shown does not necessarily total 100%.

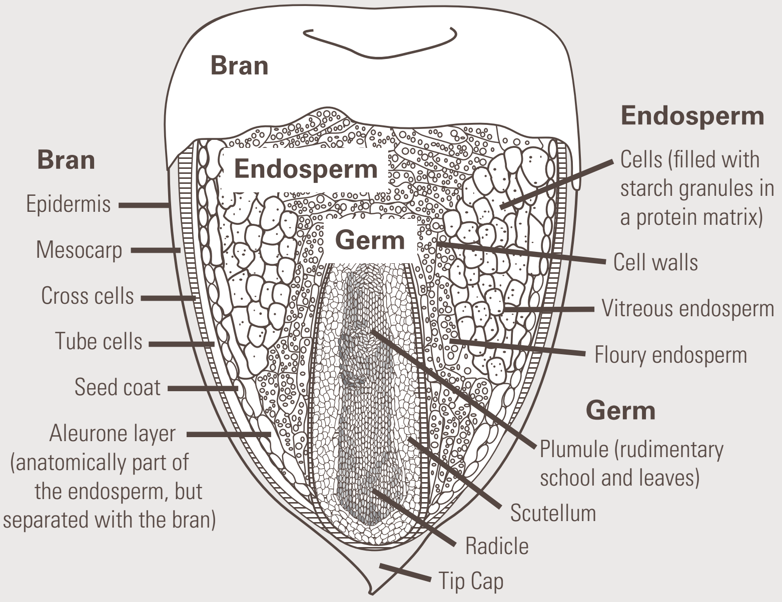

FIGURE 1 – Corn kernel anatomy, dent type. Image (modified) from Center for Crops Utilization Research, Iowa State University.

TABLE 3 – Weight and composition of component parts of yellow dent corn kernels from seven Midwest hybrids[a]

		Composition of kernel parts (%dwb)[b]				
Part	**% dry weight of whole kernel**	**Starch**	**Fat**	**Protein**	**Ash**	**Sugar**
Endosperm	82.9	87.6	0.8	8.0	0.30	0.62
Germ	11.1	8.3	33.2	18.4	10.5	10.8
Pericarp (hull, bran)	5.3	7.3	1.0	3.7	0.8	0.34
Tip cap	0.8	5.3	3.8	9.1	1.6	1.6
Whole kernel	100.0	73.4	4.4	9.1	1.4	1.9

[a] Table recreated from Watson.[9]

[b] % dry weight basis.

3.2 OATS

Oats are the sixth most significant cereal crop in the world. Global oat production between 2006 to 2010 averaged 25.8 million tons per year and was 1.4% of total cereal crop production.[12, 13] The five-year average U.S. oat production from 2004 to 2009 was 1.6 million tons per year, while the projection for 2017 U.S. oat production is 0.86 million tons. The United States is predominately an importer of oats where the average annual imports over the past 20 years have remained steady at approximately 1.6 million tons of oats per year. The average annual exports from 2004 to 2009 were 0.04 million tons.[13] This suggests that the United States will directly use or further process approximately 2.4 million tons of oats in 2017.

TABLE 4 – Oat composition (whole)[a]

Component	Dry (%)	Wet (%)
Water	—	8.2
Carbohydrate (total)	66.3	60.9
Protein	16.9	15.5
Total lipid (fat)	6.9	6.3
Fiber	9.7	8.0
Ash	1.7	1.6

[a] Table recreated from *Cereal Grains for the Food and Beverage Industry*.[12] Values presented represent averages.

Worldwide oat production has steadily declined over the past half century as the mechanization of farming has led to less of a need for horses and thus less demand for oats as a feed. Although, recent trends over the past two decades have shown stabilization of production as human consumption has become the driving force for oats production. Additionally, beginning in the 1980s there has been significant research and promotion of oats as being heart healthy, which has been an important factor continuing the drive for oats production. Oats are also used as feed for young cattle and cover crops during crop rotations.[13]

Avena sativa L. (common white oat) is the most important harvested oat variety. It is an annual variety that mostly grows in temperate climates. The overall composition of an oat grain is given in **Table 4**. Oat grains and their anatomy are depicted in **Figure 2**. The oat groat is tightly covered by a hull. The oat hull represents approximately 25–40% of the total grain mass and is mostly cellulose and hemicellulose with a small amount of lignin.[8, 12]

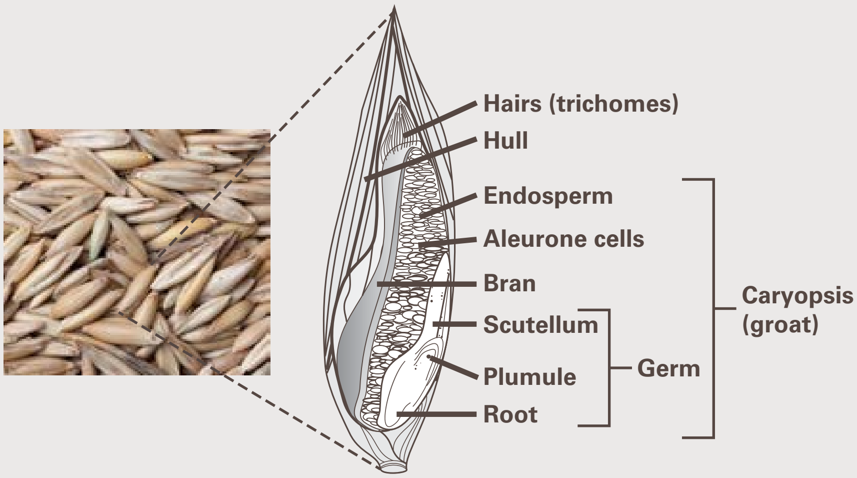

FIGURE 2 – Oat kernel anatomy. Image (modified) from Center for Crops Utilization Research, Iowa State University.

The groat is composed of three main parts with each relative mass percentage given in parentheses: bran (38–40%), endosperm (58–60%), and germ (3%). The bran consists of the outer layers of the groat, namely, seed coat, nucleus, aleurone layer, and a subaleurone layer. The aleurone cells are particularly rich in vitamins, minerals, phytate, and antioxidants. Oat bran is approximately 68% carbohydrates and fiber, 16% protein, 10% β-glucan, and 8% fat.[12] The endosperm is the primary storage site of starch, protein, and β-glucan. The oat germ (embryo) contains high levels of protein and lipids but little starch. The composition of oat grain, groat, and flour is given in **Table 5**.

Starch is the most prevalent carbohydrate component of oats comprising 40–50% of the grain. It is mainly stored in the endosperm and consists of irregularly shaped clustered granules that vary from 3 to 10 µm in size. Starch contains a small amount of non-carbohydrate components, which are lipids, proteins, and phosphorous that are complexed with the carbohydrates. Those minor constituents account for approximately 8% of the starch. The carbohydrate portion is predominately amylose and amylopectin, which represent 98–99% of the starch carbohydrates. Amylose is a polymer of α-D-glucose units bonded with α-1,4 linkages and has a relatively low degree of polymerization (~3,000) compared to amylopectin (>5,000), where degree of polymerization is the number of monomeric units in the polymer. Amylopectin is also a polymer of α-D-glucose units bonded with α-1,4 linkages but also has α-1,6 linkages that create high levels of branching in the polymer.[12]

Other carbohydrates in oats include non-starchy polysaccharides as part of dietary fiber and β-glucan. Fiber can be subdivided into water-soluble and water-insoluble fractions. The β-glucan content ranges from 2–8% of oat groats and is considered part of the water-soluble fiber. β-glucan is an unbranched linear polysaccharide of 1-4-*O*-linked and 1-3-*O*-linked β-D-glucopyranosyl units. β-glucan has been shown to have many positive health effects in humans, including reducing total blood and low-density lipoprotein cholesterol levels, inhibiting intestinal uptake of dietary cholesterol, and increasing viscosity in the GI tract.[15]

Protein accounts for 15–20% of the oat kernel. Seed proteins are classified into four types based on their solubility: albumin, globulin, prolamin, and glutelin. In oats, the predominate proteins are globulins and prolamins.[16]

Oats have a relatively higher lipid content ranging from 3.1–11.8% compared to the other cereal grains. Oat lipids are fractionated into triglycerides, phospholipids, glycolipids, free fatty acids, and sterols. Triglycerides are the main lipid component ranging from 32–85% of the total lipids. Phospholipids range from 5–26%, and lecithin (phosphatidylcholine) accounts for approximately half of the phospholipids. The major fatty acids are palmitic, oleic, stearic, and linoleic, which account for 95% of the total fatty acids.[17]

TABLE 5 – Oat grain, groat, and flour composition (dry basis)[a]

	Protein	Carbohydrate	Lipid	Fiber	Ash
Whole oat	7.7–14.8	53.0–65.8	4.3–7.6	6.5–12.8	2.3–4.2
Oat groats	21.2	39.3	15.5	5.7	—
Oat grain	8.7–16	39.0–55.0	4.5–7.2	20.0–38.0	2.1–3.6
Oat flour	15.5	—	6.2	3.6	2.1
Oat bran	18.1	44.6	9.6	15.4	3.1

[a] Recreated from Lasztity.[14]

3.3 SOYBEANS

Soybeans are a dominant oilseed in the United States and worldwide. In 2016, the United States produced 4.3 billion bushels, or nearly 130 million tons of soybeans.[18] This amounts to approximately one-third of total worldwide production for 2016, which was 387 million tons.[19] It is estimated that Iowa produced 572 million bushels or 17.2 million tons of soybeans in 2016, which is 4.4% of total worldwide production.[20]

The soybean seed is comprised of three major parts: the seed coat (hull), cotyledons, and germ (hypocotyl). The soybean is a dicotyledon seed, which are two cotyledons held together by the hull. A photograph and general schematic of soybean seeds are shown in **Figure 3**. The composition of the seed is approximately 8% hull, 90% cotyledons, and 2% hypocotyl. The chemical compositions of the components of soybeans on a dry basis are given in **Table 6**. The National Oil Producers Association gives the composition of soybeans on a wet basis as 19% oil, 36% protein, 19% insoluble carbohydrates (fiber), 9% soluble carbohydrates, 4% ash, and 13% moisture.[21]

Soybean oil is composed of triglycerides, also called triacylglycerols, with different fatty acids in its structure. A triglyceride consists of three fatty acids each attached by an ester linkage to a glycerol molecule. Glycerol is a three-carbon chain with one hydroxyl group on each carbon. The chemical structure of an example triglyceride is shown in **Figure 4**. The

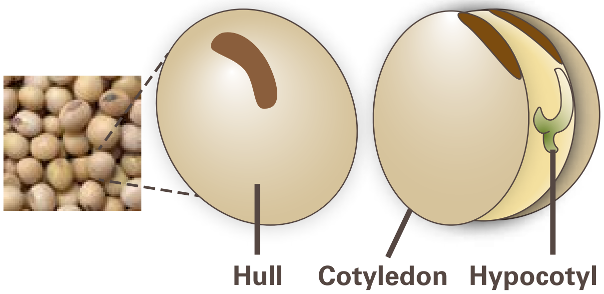

FIGURE 3 – Soybeans and main soybean components. Photograph on left from Center for Crops Utilization Research, Iowa State University.

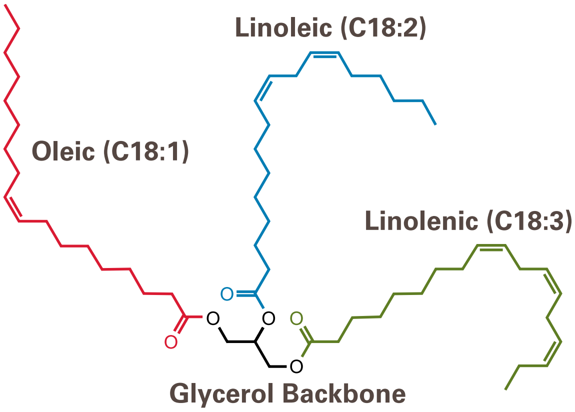

FIGURE 4 – Triglyceride structure with three unsaturated fatty acid chains. Oleic acid (red), linoleic acid (blue), linolenic acid (green). All double bonds are in the cis configuration.

TABLE 6 – Soybeans and component compositions[a] (dwb[b])

Component	Yield (%)	Protein (%)	Fat (%)	Ash (%)	Carbohydrates (%)
Whole soybeans	100.0	40.3	21.0	4.9	33.9
Cotyledon	90.3	42.8	22.8	5.0	29.4
Hull	7.3	8.8	1.0	4.3	85.9
Hypocotyl	2.4	40.8	11.4	4.4	43.4

[a] Recreated from *Practical Handbook of Soybean Processing and Utilization.*[22]

[b] dwb = dry weight basis

fatty acids of soybean oil are primarily unsaturated, meaning that they contain one or more carbon-carbon double bonds that can be further hydrogenated, or saturated, with hydrogen. The three most common unsaturated fatty acids of soybean oil are oleic, linoleic, and linolenic acid, accounting for 22.8, 50.8, and 6.8 wt% (average), respectively, of the total fatty acid content of soybean oil.[22] Their structures are shown in Figure 4 as connected to a glycerol backbone forming the triglyceride. The saturated and other minor fatty acids are listed in **Table 7**. The fatty acid chains designated in the triglyceride of Figure 4 can be any combination of those listed in Table 7.

Soybeans are approximately 35% carbohydrates, most of which is from the cotyledons. The major carbohydrates present are glucose, sucrose, raffinose, stachyose, arabinan, arabinogalactan, and acidic polysaccharides. Soybean carbohydrates are generally not processed into products for human consumption as humans lack the enzymes necessary to hydrolyze the galactosidic linkages of raffinose and stachyose. Much of the carbohydrates end up in soybean meal used as animal feed or other lower value applications.[23] The large protein content of soybeans, 40% on a dry basis, leads to a variety of products including miso, natto, soy flour, soy meal, soy protein concentrate and isolate, soy sauces, soymilk, tempeh, and tofu.

TABLE 7 – Fatty acid composition of soybean oil

Fatty acid	Fatty acid content (average wt%)
Saturated	
Lauric	0.1
Myristic	0.2
Palmitic	11
Stearic	4
Arachidic	0.2
Total saturated	16
Unsaturated	
Palmitoleic	0.3
Oleic	23
Linoleic	51
Linolenic	7
Total unsaturated	81
Total fatty acids	97[a]

[a] Individual fatty acid content values represent averages therefore the sum does not necessarily total 100%.

[b] Table recreated from Erickson.[22]

4. Manufacturing Processes

4.1 CORN OVERVIEW

There are three commercial processes for milling corn: dry milling, dry grinding, and wet milling. Dry milling is the process to physically separate the germ, tip cap, and pericarp from the endosperm creating products ultimately to be used for food products. Dry grinding is a process designed to maximize ethanol production by subjecting the entire corn kernel to fermentation. In literature and colloquial language, the term *dry milling* is often erroneously used to describe the dry-grind process.[24] The primary purpose of wet milling is to produce high purity starch, ethanol, and high fructose corn syrup. Although the most capital intensive, wet milling is often described as having an advantage over dry milling and dry grinding in that it produces a high purity corn starch slurry suitable for syrup production or high quality dry starch, while also recovering byproducts in their most valuable forms.[25] Conversely, the dry grinding process has the benefit of lower capital expense and a less complicated process, which is more amenable to smaller scale operations.

The State of Iowa leads the country in ethanol production where approximately 80% of current ethanol comes from dry-grind facilities and 20% from wet milling facilities. The 2016 production capacity of Iowa is given by the Renewable Fuels Association as 4.1 billion gallons of ethanol produced by 43 currently operating ethanol biorefineries. The total U.S. production in 2016 was 16 billion gallons, meaning Iowa accounted for over one-fourth of the total national production of ethanol.[26]

It is estimated that the corn processors in Cedar Rapids in 2016 processed nearly 250 million bushels of corn between dry grinding and wet milling, where dry grinding alone accounted for approximately 80% of the total corn processed. In 2016, corn processing in Cedar Rapids accounted for approximately 4% of total U.S. annual corn processing, which was 6.2 billion bushels.[27]

Waste production and water use by the food and bioprocessing activities in Cedar Rapids are areas where improvements in efficiencies would be substantial for city utilities and management. The sections below give further details on waste and water use; however, one notable example is water use by corn wet milling and dry grinding. Corn wet milling and dry grinding alone use approximately 2.6 billion gallons of water per year in corn processing, while the current total city usage is 17.8 billion gallons per year (City of Cedar Rapids Water Treatment Facility).

4.2 DRY MILLING

4.2.1 Process

Dry milling refers to the process of milling corn to produce products for human consumption. In 2001, corn used for dry milling accounted for less than 2% of U.S. annual corn production with U.S. dry milled corn totaling approximately 632,000 bushels (18,000 tons). Typical dry milling plants process approximately 12,000–50,000 bushels per day.[28] The typical corn dry milling process is shown in **Figure 5**.

The dry milling process begins with a truckload of corn arriving at the mill. A representative sample is taken and then analyzed for weight, moisture, corn defects (broken kernels, heat damage, etc.), foreign material, and infestation. ELISA (enzyme linked immunosorbent assay) or UV light tests are also performed to look for the presence of aflatoxin. After a general inspection and cleaning process to remove unwanted and foreign material, there are several different milling processes

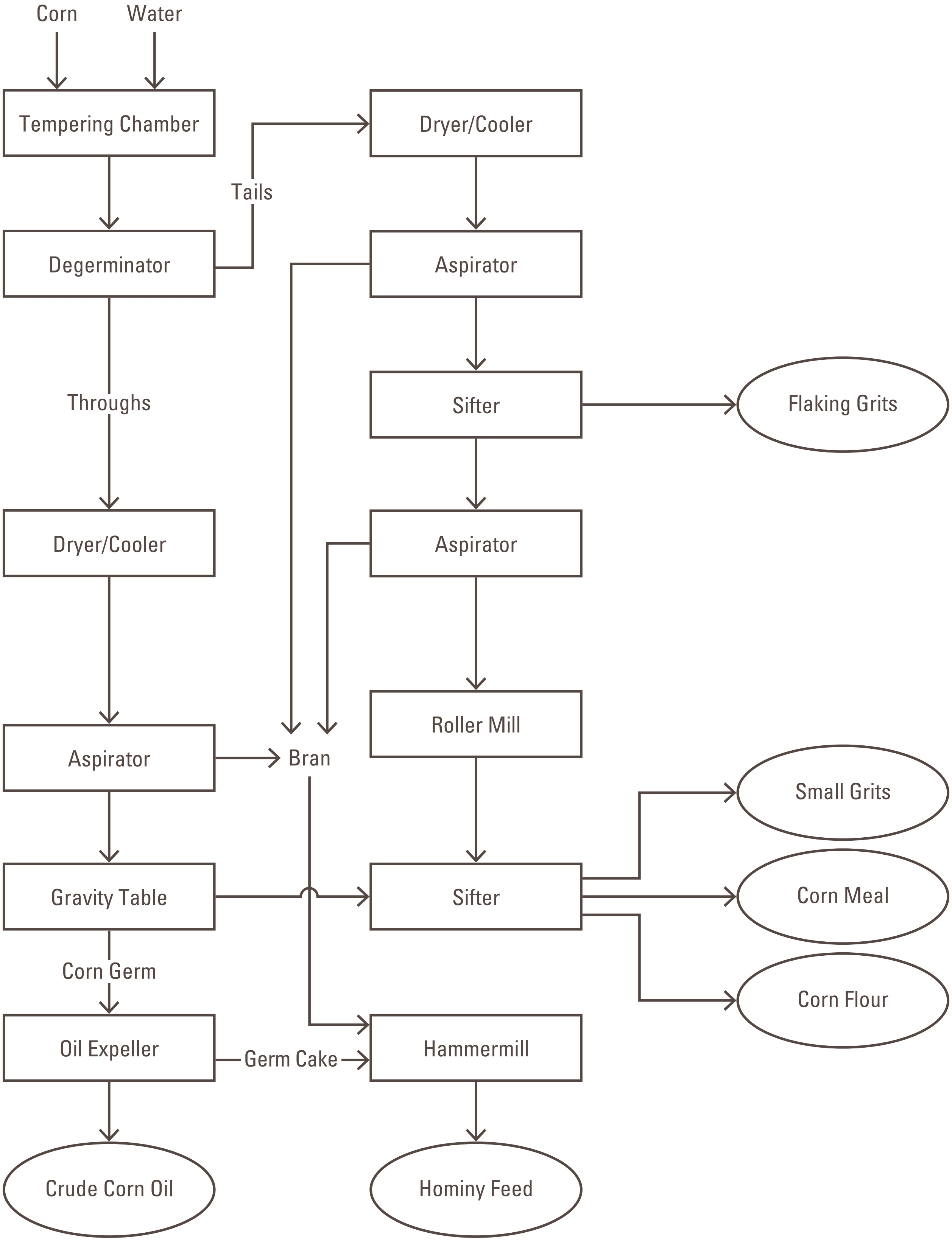

FIGURE 5 – Corn dry milling process. Adapted from Rausch et al.[24]

that can be used to grind corn kernels for human food applications.

A full-fat or non-degerming process uses millstones to grind the entire corn kernel. The product of this process is called full-fat germ meal and can be enriched with nutrients and sold as an enriched product. Full-fat germ meal can also be sold as self-rising after the addition of sodium bicarbonate, acid-reacting phosphate, and salt. The full-fat corn process is generally only seen in small mills serving local markets and in Latin America, Africa, and Asia.[28] The process to partially degerm is termed bolted milling and is typically performed with roller or hammer mills. Corn is sent through the grinder and then through a bolting, or sifting, step to remove some of the corn bran and germ reducing the crude fiber and fat content of the milled product.

The more common dry milling process is the tempering-degerming process. This involves adding moisture to the corn kernel for a controlled time and temperature to enhance the removal of the germ and bran coat. The addition of water tempers the corn aiding in fractionating and separating the corn components, the endosperm, germ, and pericarp (bran). Optimal moisture levels should be approximately 20–22%.[28] The goal of this process is to remove as much of the germ, pericarp, and tip-cap as possible leaving low-fat, low-fiber endosperm as large pieces.

After tempering the corn kernels are fed into a degerminator. The degerminator uses physical and mechanical abrasion forces to peel the germ and bran away from the endosperm while leaving the endosperm whole. The degerminator creates two exit streams, the tail stock and the through stock. The tail stock is mostly large pieces of endosperm and the through stock is composed of germ, bran, and smaller endosperm pieces. The tail stock stream is further processed to produce flaking and coarse grits. Some of this stream is further milled into smaller fractions producing brewer's grits, fine grits, corn meals, and flours. The grits and flours can be further processed using acid-modification systems, extrusion-cookers, or other systems to produce a variety of modified corn products.[28]

The through stock is processed to separate the germ from the bran and endosperm pieces. The germ is sold or pressed and subjected to hexane extraction for oil recovery. The crude corn oil is usually sold to an oil refinery. The germ cake is combined with bran, fines recovered from the through stock, and broken corn to produce a main coproduct called hominy feed, which is widely used as an animal feed.[28]

4.2.2 Products

Rausch et al. report the main products of corn dry milling to be flaking grits, brewer's grits, cornmeal, and hominy feed. Typical yields are shown in **Table 8**. The compositions of typical degermed corn products are shown in **Table 9**. The product "corn cones" is a finer granulation of corn meal. Break flour is formed from the soft floury endosperm portion of the kernel. Corn flour is made from grinding flaking grits, brewer's grits, corn meal, or corn cones and would thus have the same composition as the products shown in Table 9.[28]

Flaking grits

Flaking grits are formed from corn that is crushed and peeled before the hull, germ, and coarse meal are separated. Flaking grits can be used in breakfast cereals, brewing, flour, and snack products.

TABLE 8 – Dry milling product yields

	Yield	
Product	**lb/bu**	**kg/metric ton**
Flaking grits	6.7	120
Brewer's grits	21	380
Cornmeal	3.4	60
Hominy feed	20	350

[a] Data from Rausch et al.[24]

TABLE 9 – Composition of typical degermed corn products

Component	Flaking grits	Brewer's grits	Corn meal	Corn cones	Break flour
Moisture	13.8	11.7	12.0	11.5	12.0
Protein	7.5	7.7	7.0	8.0	6.0
Fat	0.4	0.7	0.7	0.6	2.2
Crude fiber	0.3	0.4	0.5	0.4	0.6
Ash	0.2	0.3	0.4	0.3	0.6
Carbohydrates[a]	77.8	79.2	79.4	79.2	78.6

[a] Carbohydrates determined by subtraction of other components from 100. Also called "starch by difference."

[b] Table recreated from Duensing et al.[28]

Brewer's grits

Rausch et al. give the value of brewer's grits as $240/ton in 2006.[24] The USDA ERS gives the value of brewer's grits as $187/ton in 2016. **Figure A1** gives the price of brewer's grits in the Midwest from 1983 to 2016 according to the USDA.

Cornmeal

Rausch et al. give the value of cornmeal as $314/ton in 2006.[24] The USDA ERS gives the value of cornmeal as $167/ton in 2016. **Figure A2** gives the price of cornmeal from 2002 to 2016.[5]

Corn flour

Corn flour is cornmeal that is finely ground to the consistency and texture of flour. It can be used to make a wide variety of corn-based products, including chips, taco shells, tortillas, and other snack foods.

Hominy feed

Rausch et al. give the value of hominy feed as $79/ton in 2006.[24] The USDA Agricultural Marketing Service gives the average price of hominy feed for the week of September 5, 2017, in central Illinois as $88/ton. The USDA ERS gives the value of hominy feed as $95/ton in 2015. **Figure A3** gives the price of hominy feed in Illinois from 1980 to 2015.[5]

4.2.3 Water, Energy, and Waste

There are not currently any corn processing plants in Cedar Rapids that are exclusively dry millers. Water use in a corn dry milling plant could reasonably be assumed to be significantly lower than a wet milling plant; because, as the name implies, the process is "dry," thus significantly less water is used. It would also be reasonable to assume that energy costs, on a per bushel basis, are lower since the processing steps are less complicated and less refined than corresponding wet milling steps.

4.3 DRY GRINDING

4.3.1 Process

Dry grinding is currently the primary industrial process for fuel ethanol production. The typical corn dry grinding process is shown in **Figure 6**. As mentioned earlier, dry grinding accounts for 80–90% of all ethanol production. The primary coproduct of dry grinding is distillers dried grains with solubles (DDGS). Dry-grinding coproducts, primarily DDGS, amount to one-fourth of the gross value of the ethanol industry output.[26] The dry-grind process offers advantages over the wet milling process in terms of lower capital and operating costs (including energy inputs). The number of dry grinding facilities has significantly increased over the past 15 years. In 2002, 50% of U.S. ethanol plants were dry grind, and in 2009, the fraction had increased to over 80% of all facilities.[29] In general, one bushel of corn (56 lb) will yield 2.8 gallons of ethanol, 18 lb of distillers grains, and 18 lb of carbon dioxide.

The process begins at the ethanol plant by receiving and storing corn in silos or steel bins. Plants generally keep 7–10 days of corn stored on-site. After storage, corn is sent through a coarse cleaning operation to remove broken kernels, fines, chaff, and foreign materials. Corn is then ground into either coarse meal or flour using a hammer or roller mill, with hammer mills being the most common in dry-grind plants. Grinding the corn decreases particle size and facilitates access to the enzymes and yeast of later steps. The particle size of ground corn typically ranges from 0.25 to 2.0 mm. Geometric mean diameters have been reported as approximately 0.5 mm and 0.94 mm.[29, 30] Particle size does have an effect on the amount of ethanol produced by fermentation and the amount of dissolved solids in the thin stillage.[31]

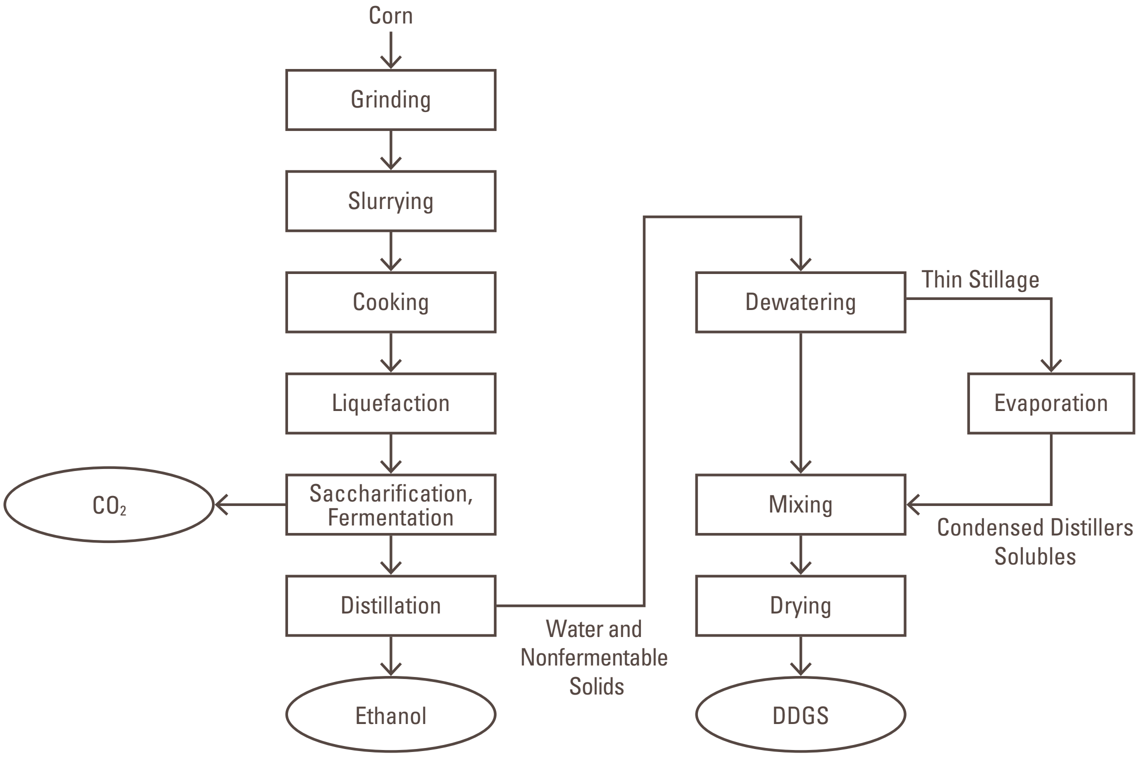

FIGURE 6 – Dry-grind process for producing ethanol and DDGS. Recreated from Liu.[29]

The next process steps are slurrying, cooking, and liquefaction. Ground corn is mixed with water to form a slurry of approximately 30% solids. The pH is adjusted throughout these steps to between 5.5 and 6.5 using ammonia, lime, or sulfuric acid. The enzyme α-amylase is added to approximately 0.04 and 0.08 wt% of the corn on a dry basis. The slurry is heated to 80–95°C for 15–20 min and is then cooked at 120–140°C for 5–10 min by injecting steam into the slurry. Cooking fully gelatinizes the starch and breaks down the crystalline structure of starch granules. The slurry is flash cooled to 85–95°C in a liquefaction tank where it is held for an additional 30–120 min. Additional α-amylase is added which hydrolyzes the long starch polymers into oligosaccharides called maltodextrins.[29]

Mash from the liquefaction step is then sent to fermentation tanks where saccharification and fermentation simultaneously occur. Saccharification is the final breakage of oligosaccharides into glucose (dextrose) monomers using an enzyme called gluco-amylase. Fermentation tanks are large vessels that can have greater than 528,000 gallons (2 million liters) in volume.[32, 33] Residence times for fermentation typically range from 40 to 72 hours. Fermentation temperature is maintained at 28–34°C. *Saccharomyces cerevisiae* is the yeast that converts glucose into ethanol, carbon dioxide, and heat. As an approximation, about 1 lb of corn will yield 1/3 lb each of ethanol, CO_2, and distillers grains. The CO_2 produced can be cleaned, compressed, and sold, but often logistics and economics prohibit this option, so plants usually scrub the CO_2 and release it to the atmosphere.[29]

The fermented liquid (beer) is sent to a holding tank called the beer well. The beer is approximately 12% or greater ethanol by volume. The beer is then sent to a distillation tower where the water and ethanol exit the top (overflow) and the solids, non-fermentable components of the corn, yeast, and some water exit the bottom (underflow). The mixture exiting the bottom of this distillation is called whole stillage.[29] The water/ethanol mixture from the overflow is sent to a rectification column and stripper to recover water and separately a 95% (v/v) ethanol solution. The remaining water in the ethanol is removed using molecular sieves, which are microporous adsorbents with a pore size that allows water to enter and adsorb but small enough to prevent larger ethanol molecules from entering the pores, thus removing water from the stream. The result is 100% pure ethanol, which is denatured and stored in tanks.

The whole stillage collected from the first distillation contains approximately 5–15% total solids (dissolved and suspended) and is centrifuged. The removed liquid is called thin stillage and the solid dewatered product is called wet cake. The wet cake is sometimes sold as distillers wet grains (DWG). The thin stillage is evaporated to produce condensed distillers solubles. These solubles are then combined with DWG and dried to approximately 10–12% moisture on a wet basis producing distillers dried grains with solubles (DDGS).

4.3.2 Products

Ethanol

Ethanol is the main product from the dry-grind process. Ethanol production in Iowa in 2016 was 4.1 billion gallons, generating $6.1 billion in gross value. It is estimated that dry-grind plants account for 80–90% of total ethanol production. **Figure 7** gives the rack price of ethanol per gallon from 1982 to the present (FOB Omaha).[34] Cedar Rapids, Iowa, has three ethanol production plants listed by the Renewable Fuels Association for 2017 with names and capacities given in **Table 10**. The Archer Daniels Midland and Ingredion plants generated approximately $900 million in gross value of ethanol alone in 2016.

Distillers dried grains with solubles (DDGS)

DDGS consists of the nonfermentable materials from the corn kernel and includes corn kernel proteins, fibers, oils, and minerals. Although these nonfermentable materials can be used to produce a variety of materials they are most commonly used for DDGS production.

Table 11 shows the nutritional composition of DDGS averaged from samples from eight nondisclosed dry-grind plants alongside an average of seven Iowa plants. In general, the component values agree, however, there is a few percent variability in the components reported (standard deviations were not given). Neutral detergent fiber is the most common measure of fiber for animal feed analysis. It measures most of the structural components in plant cells including lignin, hemicellulose and cellulose, and excluding pectin. Acid detergent fiber is a measure of the least digestible fiber portion of feed or forage. It includes lignin, cellulose, silica, other insoluble forms of nitrogen, and excludes hemicellulose.

Some dry-grind plants sell distillers wet grains (DWG), although to a much lesser extent than DDGS. Distillers grains (DDGS and DWG) often contribute between 10 and 20% of a plant's total revenue and sometimes can reach as high as 40% depending on market conditions.[29] This point is illustrated in **Figure 8**, which shows the proportion of value of a bushel of corn that is generated from DDGS production in the dry-grind process.[36] Note that Figure 8 is on a per bushel basis and is not on a price per mass basis, as in dollars per ton. The average annual price for DDGS from 1980 to 2016 is shown in **Figure A4**. The USDA ERS gives the average price of DDGS in 2016 as $106/ton. The USDA Agricultural Marketing Service gives the average price of distillers dried grains (10% moisture, 28–30% protein) for the week of September 5, 2017, in Eastern Iowa as $104/ton. The average price for wet distillers grain (65–70% moisture) for the same week was $38.50.

As DDGS is a high-volume, low-value product that is produced in Cedar Rapids and across the State of Iowa, it represents a potential source of low-cost feedstock for other applications than as animal feed. Although there do not appear to be commercialized processes for DDGS utilization other than animal feed, there are examples in the scientific literature of further processing DDGS into higher value products. Research from a group at the University of Louisville

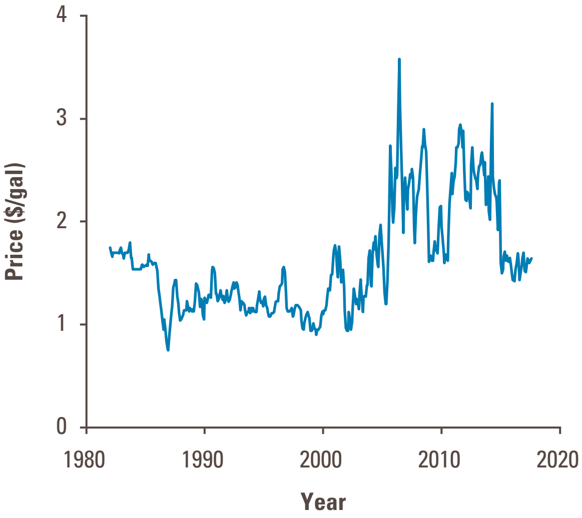

FIGURE 7 – Ethanol rack price per gallon (FOB Omaha).

TABLE 10 – Cedar Rapids, Iowa, ethanol production in 2016[26]

Company	Production capacity (mgy[a])
Archer Daniels Midland Co. Plant 1	300
Archer Daniels Midland Co. Plant 2	240
Ingredion Inc.	45
Total	585

[a] Million gallons per year

TABLE 11 – Average nutritional composition of DDGS

DDGS	%[a]	% (IA)[b]
Dry matter	91.3	88.9
Crude protein	28.4	31.2
Crude fat	10.1	10.3
Neutral detergent fiber (NDF)	33.3	n.a.
Acid detergent fiber (ADF)	11.6	n.a.
Crude fiber	n.a.	7.6
Ash	2.75	5.8

[a] Data from Urriola.[35]

[b] Data from Liu.[29]

has demonstrated high yields of xylose and arabinose carbohydrates produced from DDG using dilute acid hydrolysis, producing upwards of 300 g of sugars per kg of dry DDG. They further demonstrated isolation and recovery of xylose in high quantities from the hydrosylate.[37, 38] Cedar Rapids currently produces 540 million gallons of ethanol per year from the dry-grind process, which means approximately 1.8 million tons of DDGS is also produced. If 30% of DDGS can be converted to xylose and arabinose, this suggests 0.55 million tons of xylose and arabinose could be produced in Cedar Rapids annually. At $2,000/ton for xylose, according to Biocore, a European research program dedicated to investigating second generation biofuels and biomass derived chemicals,39 this represents an annual economic value of $1.1 billion, which is approximately equivalent to the value of ethanol produced in Cedar Rapids. The $2,000/ton price is likely assuming a high purity. Retail price for food grade xylose used as a sweetener is closer to $1,000/ton, which still represents a significant potential revenue. This supports the notion that further growth and development of the bioprocessing industry in Cedar Rapids is possible and that novel products and commercial practices can be established.

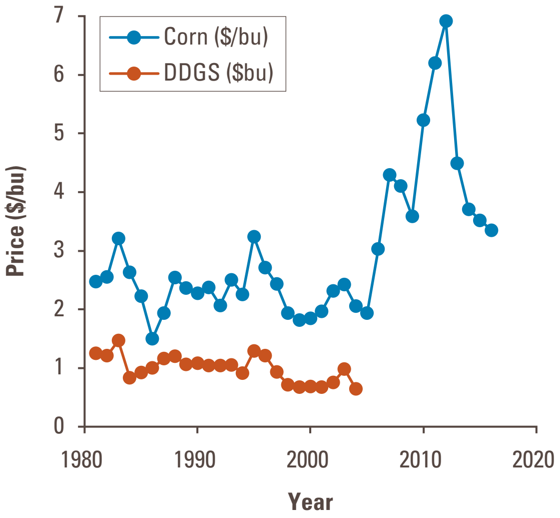

FIGURE 8 – Corn and DDGS average annual values on a per bushel of corn basis from 1981 to 2016.

An example of utilizing the solubles portion of DDGS for higher value applications than recombining with the DWG has been demonstrated by Hu et al., at the University of Minnesota.[40, 41] DDGS has high levels of phosphorous, oftentimes greater than the limits recommended for animal feed. A significant fraction of the total phosphorous is in the form of phytic acid, also known as inositol polyphosphate. In the dry-grind process, phytic acid ends up dissolved in the thin stillage, which is usually partially dehydrated and recombined with DWG to produce DDGS. Hu et al., propose a process where prior to dehydration and recombination, the thin stillage is subjected to an anion exchange process that selectively captures the phytic acid and allows the remaining components of the thin stillage to be recombined with DWG per the usual process. The phytic acid is recovered from the resin in a 25-fold higher concentration than in the thin stillage. The authors mention that phytic acid has a high economic value with applications as an antioxidant in the food industry, gastrointestinal pharmacological uses, use as an anticorrosion agent, and uses in polymer manufacturing. Retail prices of phytic acid can be found online ranging from $1,000/ton to $10,000/ton depending on the purity and supplier. This technology is at the early stages of commercialization, and again, supports the notion that further value and growth are possible in the bioprocessing industry of Cedar Rapids and the State of Iowa.

Wet distillers grain (WDG; distillers wet grain, DWG)

The USDA Agricultural Marketing Service gives the average price of wet distillers grains (65–70% moisture) for the week of September 5, 2017, as $38.50/ton.

Carbon dioxide, CO_2

Carbon dioxide is sometimes captured from the fermentation step and sold as an additional coproduct of the dry-grind process. Economic feasibility dictates if this is performed at an individual plant. If capturing, bottling, and shipping is not economically feasible for the CO_2 generated at a facility, a potential more valuable use is as a supercritical solvent for potential on-site applications. Supercritical CO_2 can be used as an effective solvent, catalyst, and extraction phase for xylose conversion to furfural, with xylose being derived from DDGS.[42] Although, high purity CO_2 (99.997%) is required for use in supercritical fluid extraction, so appropriate purification technology would be needed on-site to utilize the captured CO_2 as a supercritical fluid.

4.3.3 Water, Waste, and Energy

Water

Water use in the dry-grind ethanol production process is currently estimated as 3 gallons of water per gallon of ethanol produced by the Renewable Fuels Association. There are no publicly available records on water use by individual ethanol plants in the United States, except for the State of Minnesota, where plants have reported a range of 3.5–6.0 gallons of water consumed per gallon of ethanol produced. The average water use has declined from 5.8:1 in 1998 to 4.2:1 in 2005.[43] **Figure 9** gives the average water used in a typical dry-grind ethanol plant in gallons of water per gallon of ethanol produced.[29] There is an overall decrease in the average amount of water used from 1998 to 2008. If one uses a conservative estimate of 3.5 gallons of water used per gallon of ethanol, this would equate to over 2 billion gallons of water used annually in Cedar Rapids for dry-grind ethanol production.

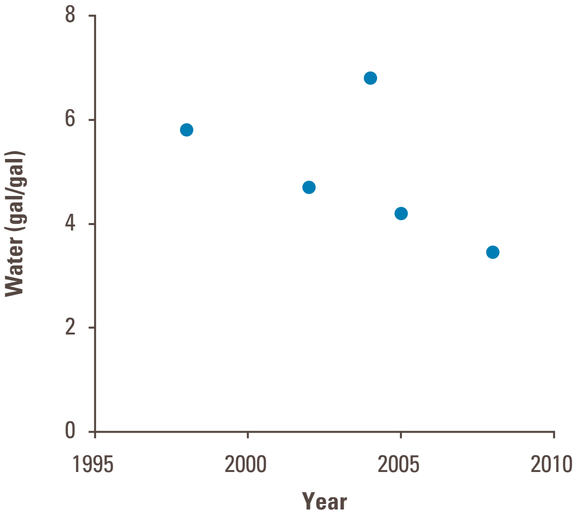

FIGURE 9 – Average water use in dry-grind ethanol plants given in units of gallons of water per gallon of ethanol produced.

Energy

Figure 10 gives the total energy, natural gas, and electricity use in dry-grind plants collected from literature sources presented in Liu et al.[29] One can see there is a downward trend in energy use in dry-grind plants from 1995 to 2008, with total energy use per gallon of ethanol being nearly halved in less than 15 years. Conversely, average ethanol production has increased from 2.53 to 2.81 gal/bu over the same time period.[29] Using the RFA estimate of ethanol produced by the dry-grind facilities in Cedar Rapids of 540 million gallons in 2016 and the data in Figure 10, the total energy used annually to produce dry-grind ethanol in Cedar Rapids is 16.8 trillion BTU. Electricity use is approximately 380 gigawatt-hours annually for dry-grind ethanol production in Cedar Rapids.

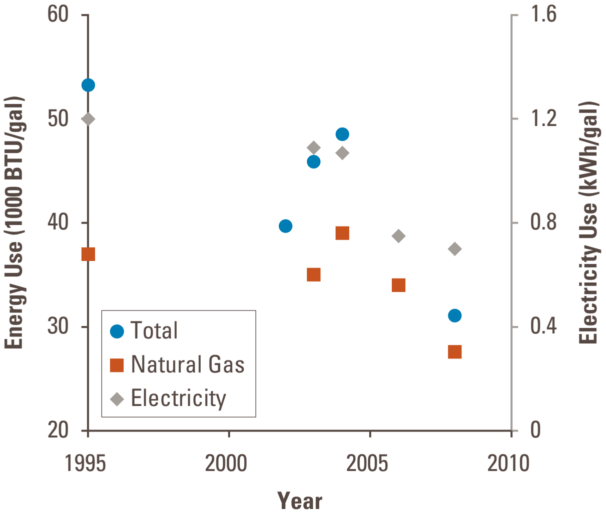

FIGURE 10 – Total energy, natural gas, and electricity use in dry-grind mills. Total energy (●) and natural gas (■) are given in units of 1000 BTU per gallon of ethanol produced. Electricity (◆) is given in units of kWh per gallon of ethanol produced.

4.4 WET MILLING

4.4.1 Process

Wet milling is a process that fractionates corn into four primary components: starch, germ, fiber, and protein. The basic processing steps are steeping, germ and fiber recovery, protein separation from starch, and washing to obtain highly pure starch.[24] The major and intermediate steps of the corn wet milling process are outlined in **Figure 11**. The numbers in Figure 11 correspond to the major steps as discussed below. The total amount of corn processed in wet milling in the United States in 2009 was approximately 1.1 billion bushels.44 Wet milling in Cedar Rapids represents a significant fraction of total wet milling in the United States at approximately 60 million bushels per year, which is 6% of the total U.S. corn wet milling processing.

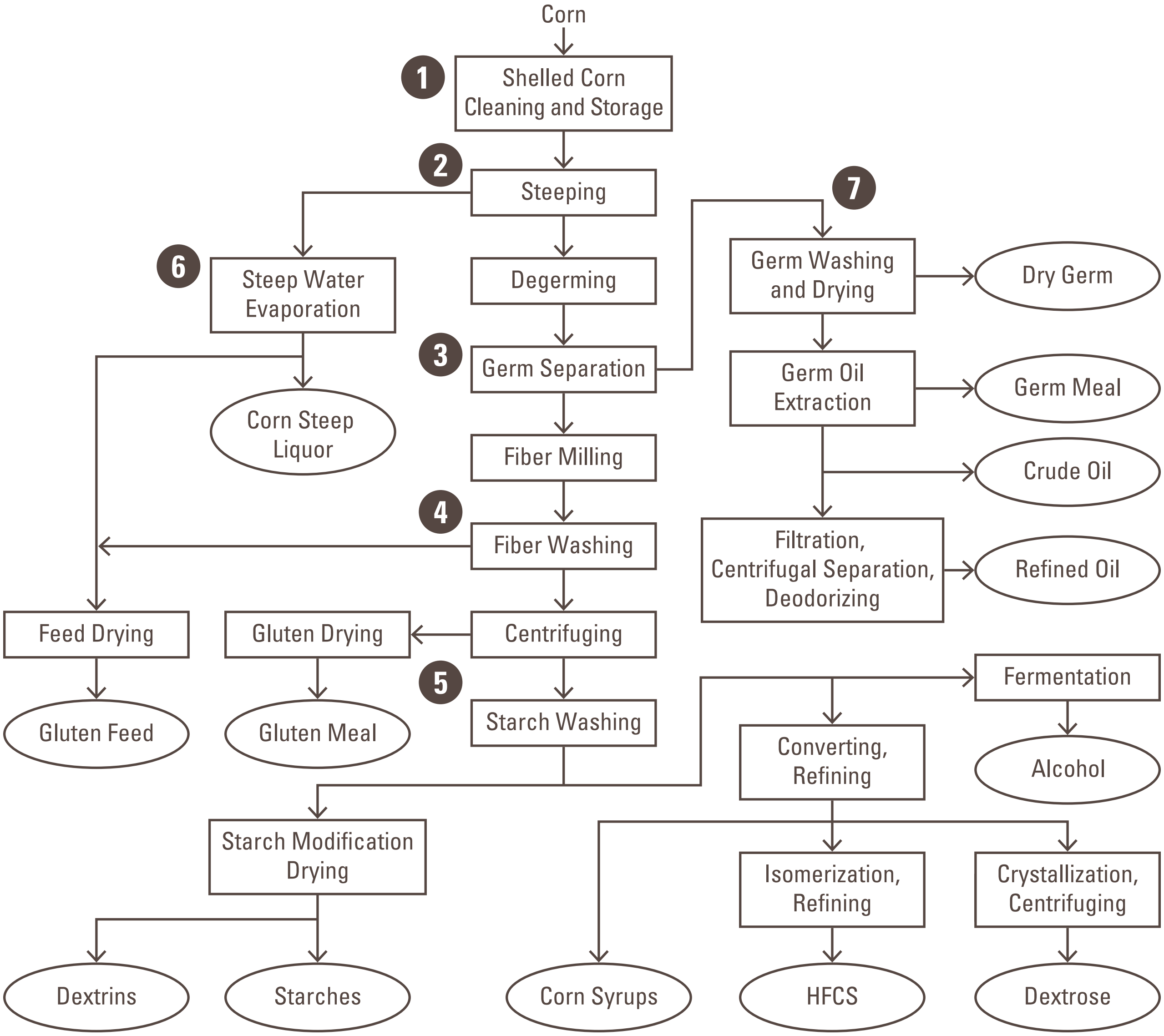

FIGURE 11 – Corn wet milling process (adapted from *Technology of Corn Wet Milling and Associated Processes*[25]). Process steps are outlined in boxes and products are outlined in ellipses.

(1) Prior to steeping, corn is cleaned to remove foreign matter including broken kernels, corncobs, stones, sand, insects, weeds, etc. This is a screening process where the digestible material recovered that is not sent to further processing is used as animal feed.

(2) Cleaned corn is steeped in water with controlled temperature, residence time, sulfur dioxide concentration (SO_2), and recirculation conditions. Cleaned corn enters steeping with a moisture content of 16 wt% and steeping increases the moisture to approximately 45 wt%.[45] Low concentration SO_2 (0.12–0.2%) is used in the steep water to act as a reducing agent to break disulfide bonds in the protein matrix surrounding starch granules. Additionally, it is used to create an environment that favors *Lactobacillus* bacteria that produce lactic acid from free sugars in the steep water. The lactic acid enhances softening of the grain, solubilizing endosperm protein, and weakening endosperm cell walls.[46] Steeping occurs in large stainless steel tanks that have capacities of 200–600 metric tons or 10,000–25,000 bushels each. The slurry is heated to 52°C and steeped for approximately 30–36 hours in total. The steeping process is a counter-current operation where there are 6–10 tanks connected in series and the steep water from one tank is sent to the next in series. The corn inlet encounters steep water that has gone through all the other tanks. The fresh steep water to the system is treated with SO_2 to the desired concentration. This method of operation allows for the newest corn to encounter the lowest SO_2 concentration where the *Lactobacillus* bacteria will be least inhibited. Overall, the amount of water used in steeping is approximately 0.9–1.2 m^3/ton of corn (6-9 gal/bushel). The used steep water contains 5–6 wt% as solids of the initial mass of corn processed. This light steep water is evaporated to approximately 50% solids and is often mixed with fiber and sold as corn gluten feed or used for fermentation.[45, 47] The evaporated light steep water is known as corn steep liquor. Considering the relatively large volumes of water used in the steeping process, studies have been performed on characterizing the steep water looking for potentially valuable products.[47, 48] One commercial example of upgrading the corn steep liquor is demonstrated by SA Bioproducts, a South African company that uses corn steep liquor as a protein food source in a specialized large-scale fermentation process to produce lysine.[49]

(3) The next step in the wet milling process is grinding and germ separation. The drained wet corn from steeping is sent to disk-type, coarse-grinding mills. The series of two coarse mills are operated to break whole kernels without breaking the soft, rubbery germs. Some additional water is added during the milling. The ground slurry from the mill is then pumped to hydroclones, where the oil-containing germ separates from the rest of the kernel because of its lower density due to high oil content. A hydroclone is similar to a cyclone where centrifugal force causes more dense particles to exit the bottom while less dense materials exit the top; however, the fluid phase is a liquid rather than a gas. The recovered germ-rich material is washed with clean water, pressed, and dried to a final moisture content of approximately 3% and either sold as-is or sent for oil extraction.[50] Normally 80–85% of the measured total oil in the corn is recovered in the germ-separation process.[45]

(4) The degermed (germ removed) corn slurry is sent across a 50 μm screen where 30–40% of the starch passes through. The remaining material is fiber, primary cell walls, and some attached starch. This mixture is milled further and screened again to remove the remaining starch. The final screening is a series of screening stages with the final stage being washed with water to remove the last of the starch. The fiber is pressed to remove most of the water, which is recycled to the fiber washing step. The final dewatered fiber is mixed with evaporated steep water and usually dried, pelleted, and sold as corn gluten feed with 18% protein content.[45] There has been some research on extracting higher value xylan, or corn fiber xylan (CFX), from the fiber recovered in this starch/fiber separation step. Hespell reports extracting 15% of the mass of the fiber as a mixture of highly pure neutral sugars. The residual fiber was still suitable for use as feed.[51] Corn fiber has also been investigated as a source of hemicellulose obtained from pretreating the fiber with alkaline solution to dissolve the hemicellulose and then hydrolyzing and fermenting the cellulose to produce ethanol.[52]

(5) The next step is to remove gluten from the mill starch. Hydroclones and centrifuges are used because of the significantly lower specific gravity of gluten (1.06) compared to starch (1.6). The separated gluten is filtered and dried to approximately 10% moisture. The final corn gluten meal is sold as animal feed with the specification of a minimum of 60% protein and 12% moisture. The starch at this point still contains approximately 5% protein and other impurities. It is sent to a series of secondary hydroclones and washed with water in a counter-current fashion. Upwards of 2.5 kg of water per kilogram of dry starch is used to remove the impurities. The final starch slurry is dried directly or further treated with chemicals depending on the final desired specifications. The washed starch should contain <0.30% total protein and 0.01% soluble protein.[45, 50, 53]

(6) The production of animal feed results from steep water evaporation, corn gluten feed from the fiber separation, and corn gluten meal from the starch/gluten separation. Evaporated steep water is added to corn fiber to produce corn gluten feed and must be dried to approximately 10% moisture. It is often pelleted to increase its density and handling characteristics. Wet corn gluten feed with 60% moisture is sometimes sold to local feeders at lower prices with the benefit of less drying expenses and environmental concerns.[45] Corn gluten meal with a moisture content of 60% is dried to 10% moisture and sold as a 60% protein product.

(7) The recovered germ from the germ/starch separation is pressed to release oil from the germ cells. The remaining germ cake is broken and flaked with roller mills and subjected to a percolating solvent extraction using hexane. The extraction removes oil to a level of less than 1.5% remaining in the germ. The solvent-extracted germ solid phase is called marc and the liquid organic phase containing the oil is called miscella. The solvent must be recovered from both phases. Hexane is evaporated from the solid germ and vacuum distilled from the liquid oil-hexane solution. Corn germ meal is the solid germ after oil and solvent have been removed and is often combined with corn gluten feed since it has a high protein content. It is not economically feasible for smaller wet mills to process germ, so they often send their germ to a centralized oil processing plant.[45]

4.4.2 Products

Typically observed optimum yields of products before refinement of the corn wet milling process are shown in **Table 12**. The 0.4 wt% loss suggests that the corn is being utilized efficiently in the process. Although 99.6 wt% of the initial mass is accounted for, the distribution of these primary corn components into the variety of byproducts is not addressed nor does it assume that maximum value is obtained in the distribution, although one might expect that the wet milling plants create a product distribution to maximize value. **Table 13** gives the mass yields per bushel of corn for the major products of the wet milling process. The following text briefly describes each primary product from the wet milling process, its composition, and respective approximate economic value, when available. Secondary products are also included. Not every plant will necessarily produce all the products mentioned; however, the list contains most products typically found in a wet milling plant. The distribution and yields of products given in Table 12 and Table 13 are indicative of the local plants in Cedar Rapids; however, one local plant reported a significantly higher yield of corn gluten feed produced, roughly 50% higher than the amount indicated in Table 13.

TABLE 12 – Distribution of corn wet milling products before further refinement

Product	Wt %[b]
Steep liquor	6.5
Germ	7.5
Bran	12.0
Gluten	5.6
Starch	68.0
Losses	0.4
Total	100

[a] Data from Blanchard (p. 73).[25]

[b] Parts of dry substance by weight per 100 parts of dry corn.

TABLE 13 – Mass yields of major wet milling products per bushel[b] of corn

	Yield[a]	
Product	(kg)	(lb)
Starch	14–14.5	31–32
Ethanol[c]	6–9	2–3 (gallons)
Sweeteners[c]	15	33
Corn gluten feed	5–6.4	11–14
Corn gluten meal	0.9–1.4	2–3
Corn oil	0.5–0.9	1–2

[a] Data from Galitsky.[54]

[b] 1 bushel = 25.4 kg (56 lb).

[c] Ethanol and sweeteners are produced from final starch product.

Starches

Starch from common corn contains 27% amylose and 73% amylopectin.[25] Amylose is an unbranched polysaccharide composed of anhydroglucose units. Amylopectin is a polymer chain of anyhydroglucose units with branched connections off the main polymer chain. Several types of final starch products are made from corn and are sold as unmodified or as one of a variety of modified types. Starches can be chemically or physically modified to suit the needs of the end product. Chemical modifications may include cross-linking of starch polymer chains and/or substituting chemical species on available hydroxyl groups. For food applications, substitutions include acetate, succinate, octenyl succinate, phosphate, or hydroxylpropyl groups. Non-food applications include hydroxyethylated and cationic substitutions. The purpose of substituting is to impart desirable changes to the properties of the starch, such as water capacity, gelling characteristics, stability (shelf-life), texture, consistency, clarity, and thermal stability. Starches may also be acid hydrolyzed to decrease the polymer chain lengths. This is termed "acid thinning" and is performed to decrease the hot-paste viscosity of the starch. Starch may also be bleached to control its whiteness and microbial counts. Starch can be enzymatically hydrolyzed to create cyclodextrins, which are cyclic oligosaccharides composed of six, seven, or eight anhydroglucose units. Starch can also be physically modified by thermally treating and/or washing with an alcohol/water mixture. Approximately 20% of total corn starch use went to the food industry in 2000.[45] **Figure A5** shows the price of unrefined corn starch sold in the Midwest from 1983 to 2015. The USDA ERS gives the average annual price of unrefined corn starch as $147/ton in 2015.[5] Starch production, including unmodified, modified, and starch used for ethanol production, can account for approximately 50% by mass of the total products produced at a typical corn wet milling facility according to a local plant in Cedar Rapids.

High fructose corn syrup (HFCS)

High fructose corn syrup is produced from the enzymatic transformation of glucose into fructose. Fructose makes a better syrup than glucose due to crystallization problems and is also much sweeter. The enzymatic isomerization of glucose reaction is generally performed until conversion yields a 42% fructose product (HFCS-42).[25] This mixture of fructose and glucose is separated using a continuous chromatographic process called a simulated moving bed. This separation produces an 80-90% fructose product, which is then blended with glucose to produce the final 55% fructose product (HFCS-55).[55] HFCS-55 has the same sweetness as pure sucrose. **Figure A6** gives the annual spot and wholesale price of HFCS-42 and HFCS-55 on a dry basis from 1994 to 2016 according to the USDA Economic Research Service. HFCS-42 and HFCS-55 had average annual prices of $754/ton and $825/ton in 2016.[56]

Corn syrups

Corn syrups is a broader category of syrups that includes HFCS as just described. This product category is also referred to as sweeteners. Types of corn syrups include 42%, 55%, and 90% HFCS, a range of syrups with DE (dextrose equivalent) 20 to 95, and 65% high-maltose corn syrup (HMCS).[9] Dextrose equivalent is a measure of the amount of reducing sugars determined by heating the syrup in a reducing solution of copper sulfate. The DE gives an indication of the degree of polymerization of starch sugars, therefore sugars with higher DE were not hydrolyzed as long as sugars with a low DE. **Figure A7** gives the price of what the USDA terms "corn syrup" from 1983 to 2016. The average annual price of corn syrup according to the USDA ERS in 2015 was $605/ton.[5]

Dextrose

Dextrose (glucose) is the fully hydrolyzed or depolymerized form of starch. It is produced from starch that is liquefied into a slurry in the presence of α-amylase that is then sent to a saccharification tank where another enzyme, amyloglucosidase, breaks the hydrolysate to dextrose levels greater than 95%. **Figure A8** shows the wholesale price of dextrose and dextrose syrup on a dry basis from 2001 to 2016 for the calendar year according to the USDA ERS.[56] The average annual price of dextrose in 2016 was $760/ton.

Dextrins (maltodextrins)

Dextrins are non-sweet polysaccharides derived from starch. Dextrins are comprised of a range of partially hydrolyzed starches produced from acid hydrolysis or a combination of acid and enzyme hydrolysis.

Ethanol

Ethanol produced in Iowa in 2016 generated a gross value of approximately $6.1 billion.[57] This figure is in total of wet milling and dry-grinding plants. If wet milling accounts for 10–20% of total ethanol production as many current literature sources suggest, then wet milling alone generated approximately $0.6–1.2 billion in Iowa and $90–180 million in gross value from ethanol production in Cedar Rapids in 2016. Based on the RFA 2016 data for ethanol production by the plants in Cedar Rapids, 45 million gallons of ethanol were produced by wet milling, which translates to approximately $68 million in gross value. Ethanol as a product at a corn wet milling facility is significant but still considered a minor product overall. In corn wet milling, ethanol accounts for approximately 15% by weight of the products, whereas in a dry-grind facility, ethanol accounts for approximately 50% of saleable products. See the ethanol product description in the dry-grind process section 4.3 for more details and prices.

Corn steep liquor

Steep water contains most of the directly soluble matter from corn in addition to products from lactic acid fermentation. Steep water is evaporated to an approximate 50% dry matter content and is usually blended with fiber to be dried as gluten feed. If there is a suitable market, the evaporated steep water can be directly sold as "condensed fermented corn extractives" for use as a special feed ingredient or industrial fermentation substrate.[25] Corn steep liquor accounts for 5% by mass of a typical corn wet milling plant's products according to survey information obtained from Cedar Rapids facilities.

Gluten feed

Gluten feed is the largest coproduct of the wet milling process in terms of volumetric production. Gluten feed contains the fiber (bran) of the corn and is often blended with steep water solids and germ meal. It is considered a medium energy, medium protein feed and is sold on a commercial basis as 18–22% protein and a minimum of

1% fat.[25] According to the USDA Agricultural Marketing Service for the week of September 5, 2017, the price of corn gluten feed pellets (21%) in Midwest states was $78.40/ton and the price of wet corn gluten feed (50–60% moisture) ranged from $30–38/ton. **Figure A9** gives the price of corn gluten feed in the Midwest from 1980 to 2015. The average annual price of corn gluten feed in the Midwest in 2015 was $96/ton.[5] Gluten feed accounts for approximately 33–35% % by mass of a typical corn wet milling plant's products according to survey information obtained from Cedar Rapids facilities.

Gluten meal

Gluten meal is a high protein material separated from starch. The final corn gluten meal is sold as animal feed with the specification of a minimum of 60% protein and 12% moisture. The centrifugal separation of gluten and starch described in step 5 in the process section can achieve protein levels over 70%, so low grade starch is often mixed with the gluten meal to obtain the final specifications.[25] According to the USDA Agricultural Marketing Service for the week of September 5, 2017, the price of corn gluten meal in Midwest states was $474.35/ton. **Figure A10** gives the price of corn gluten meal in the Midwest from 1980 to 2015. The average annual price of corn gluten meal in the Midwest in 2015 was $487.[5] Gluten meal accounts for approximately 4% by mass of a typical corn wet milling plant's products according to survey information obtained from Cedar Rapids facilities.

Oil, crude, and refined

Corn oil is the most valuable byproduct obtained from corn. It is obtained from the germ by mechanical expelling using screw presses or a combination of presses and solvent extraction using hexane. Using a screw press alone removes approximately 80% of the available oil in the germ and additionally using hexane extraction recovers a total of approximately 97% of the available oil. Crude corn oil is a mixture of triacylglycerols and extraneous components including free fatty acids (FFA), phospholipids, color bodies, odors, flavors, pesticides, aflatoxin, metals, oxidative byproducts, and milling residues.[45] The refining process consists of filtration, degumming, caustic treatment, bleaching, winterizing, hydrogenating, and deodorizing. Phospholipids are removed during the degumming step and are dried and sold as a coproduct called lecithin. Lecithin is used as an emulsifier, antioxidant, nutrient, and dispersant. The USDA reports the average price for crude corn oil in Iowa in 2017 (January–September) as $0.281/lb or $562/ton ($620/metric ton). The USDA Agricultural Marketing Service for the week of September 5, 2017, gives the price of crude corn oil in Midwest states as $0.3675/lb or $735/ton ($810/metric ton). **Figure A11** gives the average annual price of corn oil in the US from 1994 to 2015. The average annual price of corn oil in the United States in 2015 was $0.3925/lb, or $785/ton.[58] Corn oil amounts to 1–2 pounds per bushel of corn processed. For Cedar Rapids corn processing, this is approximately 1.7– 3.4 million tons of oil per year.

Germ meal and dry germ

Germ meal is the product left after the extraction of oil from the germ. Germ meal has a high protein content and is sold as a medium energy component of feed for hogs and poultry. In general, germ meal contains 25% protein on a dry basis and 1.5% oil if solvent extraction was performed or approximately 10% if not.[25] Germ meal accounts for approximately 6% by mass of a typical corn wet milling plant's products according to survey information obtained from Cedar Rapids facilities.

4.4.3 Water, Waste, and Energy

Water and waste

Although several of the processing steps in wet milling use considerable amounts of water, the general principle of water use in the entire plant is a countercurrent operation relative to the input of the corn kernel. Clean water is first used in the final product-finishing operations and is sent upstream to washing and steeping steps as process water. This minimizes the overall total input of water to the system. In 1988 the average water consumption of a wet milling plant was 1.5 m^3 per metric ton of corn.[59] This amount of water seems to be a reasonable estimate considering the steeping described above in the process steps uses 0.9–1.2 m^3 per metric ton of corn. Steeping is close to the last, if not the last, step in the wet milling process where process water is used. Water consumption of 1.5 m^3/metric ton of corn is equivalent to 10 gallons per bushel of corn. With corn wet milling in Cedar Rapids currently processing approximately 60 millions bushels per year, this calculates to be 600 million gallons of water used per year for wet milling in Cedar Rapids.

Corn wet milling is a mature process with advanced technologies that have been refined for decades to maximize production and minimize water use and waste produced. Based on numbers provided by a corn wet milling plant in Cedar Rapids, solid waste produced represents only approximately 0.1% of the total products based on mass. Corn wet milling plants in Cedar Rapids have described the composition of solid waste as one-third calcium sulfate and two-thirds general process waste and trash, where the general process waste consists of scrap feed products.

Energy

The proportions of total energy use for the major functions are shown in **Figure 12**.[54] The estimated energy consumption for the major operations in a wet milling plant are given in **Table 14**.[54] These numbers are based on a 100,000 bu/day facility operating 24 hours per day. The wet milling plants in Cedar Rapids are approximately this scale of operation. From these data, one can see that a significant percent of the total energy in a wet milling process is dedicated to dewatering, evaporation, and drying operations. It is worth noting the significant reduction in total energy used per bushel of corn processed in wet milling over the past 40 years. In the 1970s the energy use was approximately 200,000 BTU/bushel, whereas in 2007 the energy use ranged from 114,000 to 143,000 BTU/bushel.[36] This nearly 50% reduction in energy use is attributed to modern energy-saving technology and process optimization.

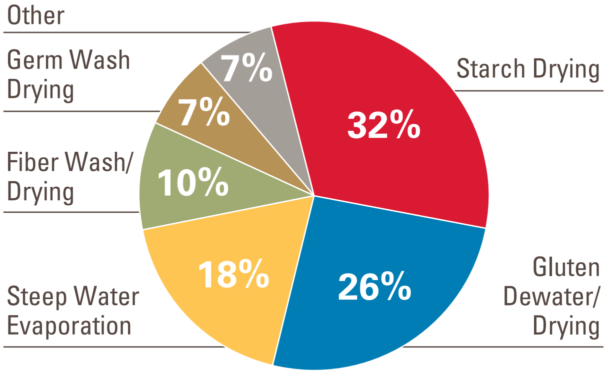

FIGURE 12 – Proportional energy use for major steps in wet milling process.

TABLE 14 – Estimated energy consumption in corn wet milling based on a 100,000 bu/day facility

	Energy consumption	
Operation	**kJ/bu**[b]	**BTU/bu**[b]
Corn receiving	1370	1300
Steeping	4010	3800
Steep water evaporation	22300	21100
Germ recovery (1st grind)	2220	2100
Germ recovery (2nd grind)	1160	1100
Germ recovery (washing)	106	100
Germ dewatering and drying	8550	8100
Fiber recovery	6960	6600
Fiber dewatering	1270	1200
Protein (gluten) recovery	3300	3100
Gluten thickening and drying	5380	5100
Starch washing	1580	1500
Starch dewatering and drying	37100	35200
Gluten feed dryer	26800	25400
Total	122400	116000

[a] Data from Galitsky.[54]

[b] 1 bushel = 25.4 kg (56 lb).

4.5 OATS

Oats production and price per bushel from 1975 to the present are given in **Figure 13**. A bushel of oats is 32 pounds with 14% moisture. Although the price of oats has trended upward over this period, production has steadily decreased. As noted earlier, this is largely due to the decrease in demand for oats as horse feed. As an example, in 2007 Quaker Oats reported on their website that the plant in Cedar Rapids generates 40,000 tons of oat hulls per year.[60] Oat hulls represent approximately 30% of the total grain by mass, therefore the plant processed approximately 133,000 tons of oats (8.3 million bushels) in 2007. It should be noted that oats processed at the Quaker Oats plant in Cedar Rapids are of a unique variety that grows exclusively in Canada, specifically the provinces of Saskatchewan and Manitoba, due to their desirable milling quality.[61, 62] The total oats produced and net imported to the United States was 3.1 million tons (193 million bushels) in 2007.[5] Thus, in that year, Quaker Oats in Cedar Rapids processed 4% of the total available oats in the United States in 2007. It is estimated that Quaker Oats currently processes approximately 450,000 tons, or 28.5 million bushels, of oats per year. The United States will produce approximately 54 million and import 100 million bushels of oats in 2017, thus Quaker Oats in Cedar Rapids accounts for over 18.5% of total oats processed in the United States in 2017.[5] As shown in Figure 13, oat production in the United States has steadied over the past decade and oat imports have been relatively constant at approximately 100 million bushels per year over the same time period. This observation supports the increasing importance of oats processing in Cedar Rapids as it has increased from 4 to 18.5% of total U.S. oats over the past decade. There are additional manufacturers in Cedar Rapids that process oats, however the majority of oats processing occurs at the Quaker Oats facilities.

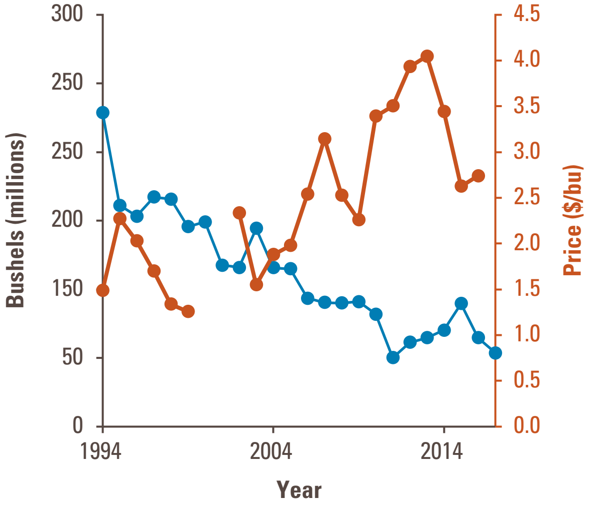

FIGURE 13 – Oats production (U.S.) and average annual price (Minneapolis, Minnesota).

4.5.1 Process

The flow diagram for oats processing is shown in **Figure 14**.[12] Oats can be stored up to a year under proper storage conditions: 20°C, 12–14% moisture, and protection from pests and fungi. From storage the oats go through a cleaning process to remove foreign material using an aspirator, a sieving separator, and a magnetic separator. The cleaned oats are then graded using sieves where they are separated into two to four fractions based on size. The oat kernel is enclosed in the hull; therefore, the hull must be removed before further processing. Unlike other grains, the kernel and hull are not fused together so the hull can be removed rather easily. The hull and groats are separated using impact or stone-hulling systems where groat breakdown is minimized. After the hull and fines are removed, the groats are heat-treated in a kiln. Heat treatment inactivates several types of enzymes that cause rancidity and bitterness and reduces bacteria and mold levels. The groats are graded where smaller groats are cut using a rotary granulator and milled to flour or rolled into flakes. Fines and remaining hull pieces are removed using an aspirator. Larger groats from the grading are rolled into higher quality flakes or ground into flour.[12]

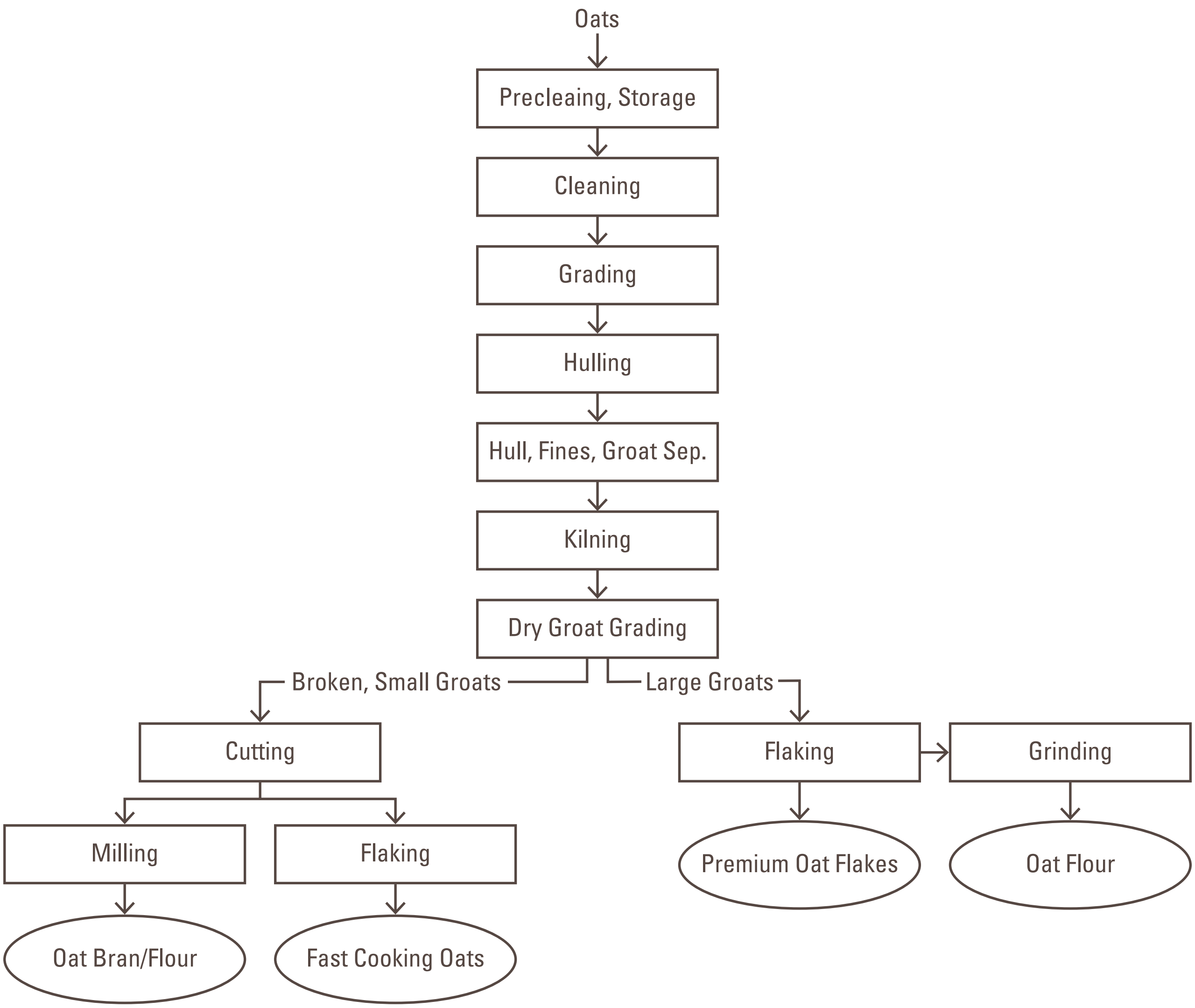

FIGURE 14 – Oats processing flow diagram. Recreated from Cereal Grains for the Food and Beverage Industry.

4.5.2 Products

Oats have been consumed as food products for centuries and have several food applications. In 1997 the U.S. Food and Drug Administration (FDA) approved of the health claim for the benefits of soluble fiber from oats. This approval has created a growing demand for healthful oat food products. Oats are used in the production of hot cereals, ready-to-eat cereals, bakery products, cookies, infant foods, and a small range of beers.[12] The percentages of total oats production given for each of the products listed below were compiled by surveys from plants in the Cedar Rapids region.

Oat bran

Oat bran is used to produce hot and ready-to-eat cereals. Oat bran is regarded as a highly nutritive product. Oat bran accounts for approximately 0.12% of total oats processing. The retail price of oat bran is approximately $2/lb, or $4,000/ton.

Oat flour

Oat flour is used to produce ready-to-eat (RTE) cereals, which represent the second largest product category for oats. Oats for RTE cereals are processed in a variety of methods including toasting, rolling, puffing, shredding, and extruding. Oat flour can also be blended with corn flour to produce RTE products. Oat bread doughs are also made from oat flours.[12] Oat flour accounts for approximately 14% of total oats processing. The retail price of oat flour is approximately $3/lb, or $6,000/ton. The bulk price of oat flour is $365/ton at Grain Millers, Inc. in Eden Prairie, Minnesota.[63]

Fast cooking oats

Hot cereal is the most popular food product made from oats. Hot oat cereals are also referred to as instant oats, quick oats, or fast cooking oats. Fast cooking oats are usually pre-cooked, dried, and rolled or pressed slightly thinner than rolled oats.[12] Fast cooking oats account for approximately 7% of total oats processing. Fast cooking, a.k.a. instant oats, retail for approximately $2.50/lb, or $5,000/ton.

Premium oat flakes

Hot cereals are also produced from rolled oats (whole oat flakes), but to a lesser extent than the fast cooking or instant oats. Oat flakes are also used to make granola, snack bars, cookies, and other products. Whole oat flakes are used in a variety of baking products, where the texture of the whole oat is desired over the finer texture of the fast cooking oats.

Oat hulls

Oat hulls represent nearly one-third of the total oat grain by mass and are described as a challenge for byproduct utilization.[64] The hulls are approximately 30–35% fiber, 30–35% pentosans, 10–15% lignins, and the remainder is protein and ash. The hulls can be finely ground and used as animal or human food ingredients. Alternatively, oat hulls have recently been used as a fuel source in power plants. One example is Quaker Oats sending its hulls to the University of Iowa replacing coal as a fuel source and supplying over 10% of the university's energy needs.[64] The Quaker Oats plant in Cedar Rapids, Iowa, produced approximately 40,000 tons of oat hulls per year in 2009.[60] Another example is the General Mills plant in Fridley, Minnesota, where since 2010, it has been burning 10% of their oat hulls in a biomass boiler that provides 90% of the steam used to heat the plant and make oat flour. The ash from the burned oat hulls is used as a soil nutrient on nearby farms. The remainder of their hulls are sold to several partners at an average rate of two trucks per hour, 24/7. One of their partners is Koda Energy in Shakopee, Minnesota, that burns oat hulls supplying energy to power their plant, a neighboring company, and 8,000 nearby homes.[65] Total oat hull production at the Fridley plant is quoted as 2,000 tons per year.[66] Oat hulls accounts for approximately 32% of total oats processing. The market value of oat hulls is $50/ton.

Feed oat meal

Feed oat meal accounts for approximately 9% of total oats processing. The price of feed oat meal given by Grain Millers, Inc. in Eden Prairie, Minnesota, is $375/ton.[63]

Oat groats

Oat groats accounts for approximately 27% of total oats processing. Whole oat groats retail for approximately $1.12/lb, or $2,240/ton.

4.5.3 Water, Waste, and Energy

Water and energy use in an oats processing plant will, at a rough approximation, be similar to a corn dry milling plant on a per ton of seed-processed basis. In current operations, solid waste produced by an oats processing plant in Cedar Rapids was 0.14% by mass of the total products.

4.6 SOYBEANS

The annual soybean production and gross value generated in the United States from 1960 to 2016 is shown in **Figure 15**. There has been an almost linear increase in soybean production in the United States since 1960 with concomitant increase in gross value in relation to annual prices.

Production of soybeans in Iowa totaled 572 million bushels in 2016, which is 13.3% of total U.S. production. The amount produced in Linn county was 6.1 million bushels harvested from 101,000 acres, which is 1.1% of total Iowa production and 0.14% of total U.S. production in 2016. At $9.51 average price per bushel in 2016, Linn county soybean crop production generated $58 million in gross value. Soybean yield in Linn county was 60.5 bu/acre, which is approximately the state average yield.[67]

In 2017, there were two soybean processing facilities located in Cedar Rapids, and according to industry experts, the facilities processed approximately 100,000 bushels per day in total, or 36.5 million bushels per year. That represents approximately 6.4% of the total soybeans harvested annually in Iowa.

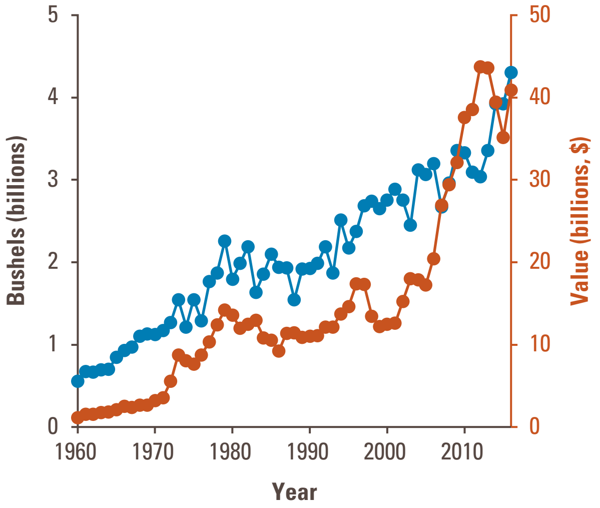

FIGURE 15 – U.S. soybean production and gross value.

4.6.1 Process

The typical soybean process is outlined in **Figure 16** with the following numbered sections corresponding to the numbered operations in the process flow diagram.

(1) Soybean production begins with harvesting, cleaning, drying, and potentially storing if the soybeans are not immediately transferred to a commercial elevator. The soybeans can be sold with varying amounts of moisture, however 14% moisture is a common specificiation.[22] Once the soybeans are transported to a plant, they are prepared for extraction. The first step is to dry the soybeans to a moisture content of 10%. The soybeans are cleaned again by passing through a magnetic separator and screen to remove remaining foreign material.[68]

(2) Next, the soybeans are cracked into 4–6 pieces using cracking rollers. The intention is to break the soybean into suitable pieces for dehulling and flaking. The soybeans are then dehulled to produce high-protein meal for animal feed or flour for human use. Soybeans contain approximately 8% hulls by weight. The extent of dehulling, if any at all, depends on the quality and amount of protein desired in the meal. The subsequent extraction process is not majorly affected if dehulling is not performed. An alternative method to conventional dehulling is hot dehulling, which is performed before cracking and flaking. The benefit of this is overall energy savings due to combining drying into this dehulling operation.[69]

(3) The soybean fragments are then conditioned with heat and steam. The final operation that is traditionally performed before extraction is flaking the soybean fragments using roller mills to a particle size of approximately 0.01–0.012 inches.[69]

(4) Extraction is the next major processing step where the soybean flakes are flowed counter-currently with an extraction solvent, hexane. Hexane is a good solvent for oil, so the oil from the soybean flakes transfers into the organic hexane phase. An extractor provides the means for physically contacting the flakes and the solvent. There are several types of extractors that can be used, including a rotary or deep bed extractor, a basket extractor, a horizontal conveyer belt extractor, a continuous loop extractor, among others. Hexane with dissolved oil is referred to as miscella.[69] Other solvent and extraction methods have been researched, however hexane extraction remains the common commercial practice.[70, 71]

(5) The solvent must then be recovered from the miscella and from the hexane saturated soybean flakes. Solvent is recovered from the miscella using two evaporators and a steam stripper. This step is listed as "oil distillation" in Figure 17. Steam and solvent vapors are condensed and separated. Solvent vapors that are present in vented air are recovered using a mineral oil absorption process. Overall solvent loss for the operation is estimated to be 0.5–1.0 gallons of solvent per ton of soybeans processed.[69]

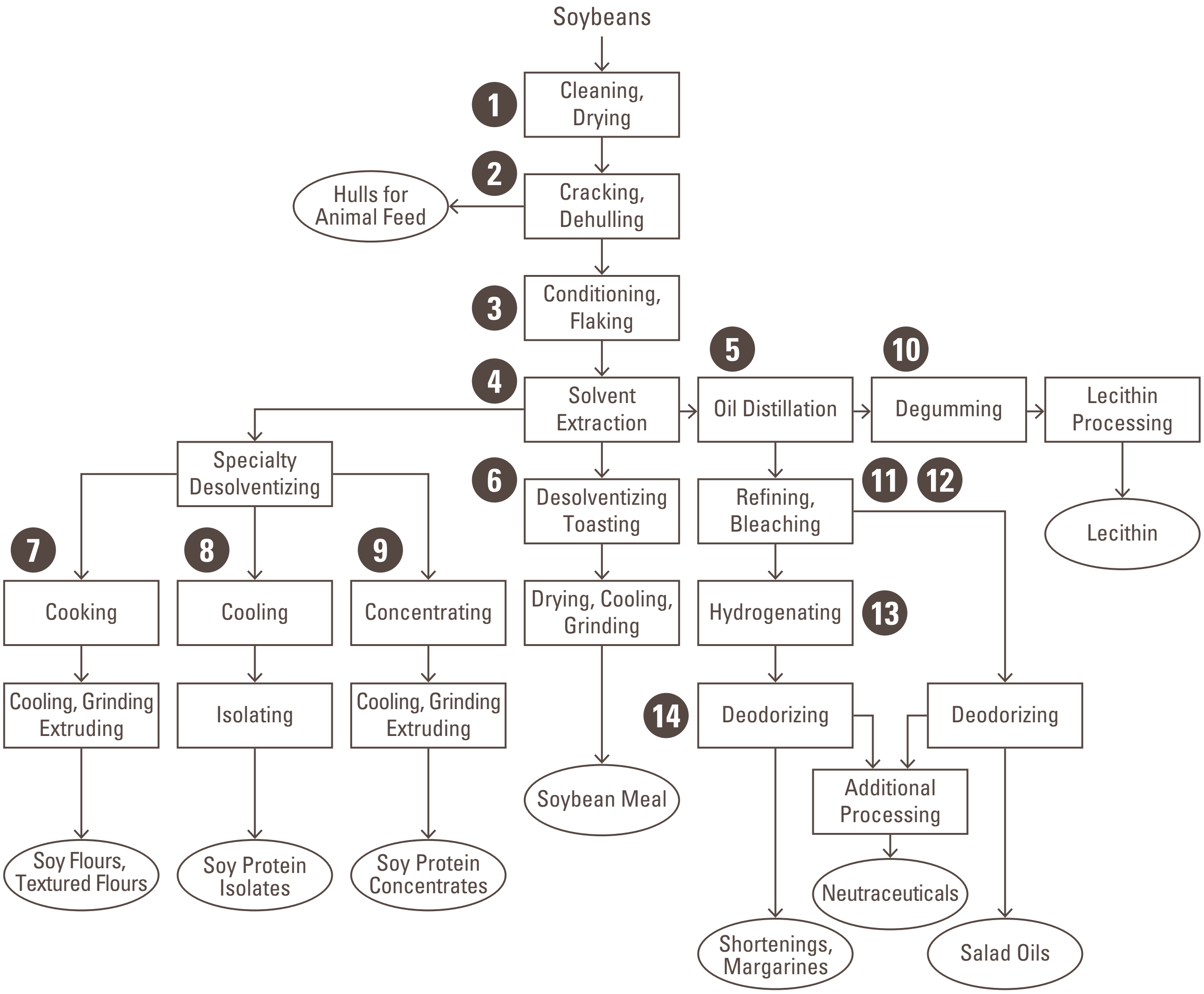

FIGURE 16 – Soybean processing flowchart. The numbers listed in the flowchart correspond to the numbered paragraphs in this section. The steps are not necessarily performed sequentially as numbered. Recreated from National Oilseed Processors Association.[84]

(6) Solvent must also be recovered from the flakes, which contain approximately 30% hexane, and occurs in an operation called desolventizing-toasting. The toasting aspect is necessary to produce acceptable meal for animal feed. Although toasting is generally thought of as a dry heating process, soybean flake "toasting" is better described as cooking at elevated moisture levels. A desolventizer-toaster (DT) is a multi-trayed chamber where steam is injected and flowed through the flakes at 70°C. Some steam condenses in the meal and aids in "toasting." The remainder is condensed as it exits the DT and is used as a heat source for the first evaporator in the extractor unit. The cooked meal contains about 20% moisture and is dried, cooled, and ground into a final soybean meal product.[72]

(7) The specialty desolventing steps shown in Figure 17 refer to processing edible soybean products other than animal feed meals. Examples of products include full-fat or defatted soy flours and grits, refatted or lecithinated flours, soy protein concentrates, soy protein isolates, dried soy milks, tofus, extruder-texturized flours and concentrates, and other specialized products. Full-fat soy flours are prepared from dehulled soybeans which have not undergone extraction where three types are produced: enzyme-active, toasted, and extruder-processed. Soy protein products are often sold as bulk ingredients for further food production uses. Most soy protein products are made from hexane-defatted soybean flakes, also called white flakes. The white flakes can be sold without modification or further milled to flours. Flours can be refatted or re-lecithinated to add some fat or improve flour dispersion in final products, respectively.[73]

(8) Soy protein isolates can be produced by several methods including: pH extraction-precipitation, molecular weight separation with ultracentrifuge, membrane processing, salt extraction, and other less used techniques. Using a reverse osmosis membrane process for dewatering the isolates can offer significant energy savings. Most isolates are produced by extraction, re-precipitation, and neutralization with the intent of removing insoluble fiber and further washing the proteins of non-protein solubles.[73]

(9) Soy protein concentrates contain at least 65% protein and less than 10% water. They can be produced by extraction of the white flakes with an aqueous ethanol solution to remove solubles, acid-leaching to remove soluble sugars while retaining insoluble proteins, and hot-water leaching to denature the proteins and remove water solubles. A detailed procedure and processing characteristics, such as yield and protein content, and protein functional properties for soy protein isolates and concentrates are given by Wang et al.[74] Uses of soy protein concentrates include applications requiring a low-flavor profile, water- and fat-absorption, emulsification, and other nutritional uses.[73]

(10) Lecithin is a mixture of phospholipids, primarily phosphatidylcholine, phosphatidylethanolamine, and phosphatidylinositol. Phospholipids have a chemical structure similar to triacylglycerols, consisting of a glycerol backbone (3 available carbons) with two fatty acid constituents and the third carbon having a phosphatidyl group. There are four primary steps to producing lecithin from crude soybean oil: hydrating, separating, drying, and cooling. The hydrating step involves mixing 1–3% water with the oil at 50–70°C. The phospholipids have a polar phosphatidyl group that will hydrate within one hour and form a gum denser than the oil. The lecithin gums are separated by centrifuging, leaving a crude oil with a maximum phosphorous content of 100 ppm where the original crude oil had approximately 1,000 ppm. The recovered lecithin gums contain approximately 50% water and a maximum of 17% oil. The lecithin is then dried to a moisture content <1% and cooled to 20–30°C where it can be stored for over a year without changes in quality or properties.[75]

(11) After the lecithin has been removed from the oil, the next processing step is neutralization, which is also termed deacidification, caustic refining, or steam refining. The purpose of neutralization is to react free fatty acids (FFA) with an alkaline compound (sodium hydroxide, NaOH) to create soaps (saponification). The soaps then adsorb color and precipitate any gums or water-soluble components present in the oil. The mixture is heated and agitated for a defined period and then centrifuged to separate the aqueous phase from the oil phase. The amount of caustic (NaOH) added is proportional to the amount of FFA in the oil plus a slight excess.[76]

(12) After neutralization the oil is bleached to reduce levels of pigments, oxidation products, phosphatides, soaps, and trace metals. Removing these components improves the flavor of the final oil. The bleaching process involves adding an amount of earth (adsorbent) to the oil, heating to a bleaching temperature, and then filtering out the spent adsorbent. Types of earth used include natural clays, acid-activated clays, activated carbon, and silicates. Bleached oils must be sent directly to hydrogenation or deodorizing as they are susceptible to oxidation.[77]

(13) Neutralized and bleached oil is then ready for hydrogenation, which is the process used to increase the crystalline fat content of edible oils and impart resistivity to thermal and atmospheric oxidation. The basic hydrogenation reaction can be viewed as adding hydrogen to an unsaturated carbon-carbon bond in a fatty acid. If all the double bonds in an unsaturated fatty acid undergo hydrogen addition, then it is called a saturated fat. Besides reducing the level of unsaturation in the fatty acids, the formation of geometric and positional isomers also occurs creating the infamous trans fats. The level of unsaturation in oil has historically been measured using iodine value (IV). The traditional commercial catalyst used for oil hydrogenation is nickel, although other platinum group metals have been explored. Hydrogenation is a three-phase reaction (solid catalyst, liquid oil, gaseous hydrogen) that is commonly performed in batch slurry reactors. Continuous flow reactors are also used to some extent when larger volumes of oil need to be processed. A thorough review of vegetable oil hydrogenation is given by Veldsink et al., where they discuss several factors of hydrogenation such as catalyst identity, reactor configuration, reaction conditions (temperature, pressure, catalyst loading), reaction mechanism steps, reaction rate and selectivity, and mass transfer resistances.[78] Although oil hydrogenation has been performed for over a century, it is still an active area of research.[79] Mass transfer of hydrogen from the gas phase into the liquid phase and then transfer to the active catalytic sites on the solid catalyst surface is often given as the rate-controlling step in vegetable oil hydrogenation. An example of research investigating hydrogen mass transfer and the development of a new type of reactor to overcome the mass transfer limitations is described by Singh et al. and Wales et al.[80-82] In their research they used a gas/liquid phase contacting membrane to act as a hydrogen deliverer to catalytic sites integrated on the membrane surface, thus avoiding the necessity of bulk dissolution of hydrogen gas in the liquid phase. This method of hydrogen delivery prevented hydrogen starvation at the catalyst, which is the mechanism for producing trans fats isomers, thus improving the selectivity of the secondary isomerization reaction.

(14) The final primary step after hydrogenation is deodorizing. After deodorizing the oil is generally ready for use as an ingredient in margarine, shortening, salad oil, cooking oil, butters, and many other food products. Deodorization is a steam stripping process conducted under vacuum pressure. Steam at a temperature of 252–266°C is injected into the oil for a holding time of 15–60 minutes. The pressure of the system is kept between 1–6 mmHg (1.3–8 mbar) absolute pressure. The elevated temperature and low pressure cause volatile chemical species to vaporize and exit the system with the steam. The elevated temperature also causes decomposition of carotenoid pigments, thus improving the color of the final oil.[83]

4.6.2 Products

The soy products list given below is not exhaustive, however it covers the main classes of products that come from soy processing and those that the USDA tracks as commodity products.

Soybean oil

Average annual and monthly soybean oil prices are given in **Figure A12**. In 2016, the USDA ERS gives the average annual price of crude soybean oil as $588/ton.[85]

Soy flours

Soy flours include full-fat or defatted soy flours and refatted or lecithinated flours. Full-fat soy flours are prepared from dehulled soybeans which have not undergone extraction where three types are produced: enzyme-active, toasted, and extruder-processed. However, most soy protein products are made from hexane-defatted soybean flakes (white flakes). The white flakes can be sold without modification or further milled to flours, which can be refatted or relecithinated.[73] Soy flour is approximately $150–200/ton.

Soy protein isolates

Soy protein isolates (SPI) are the extracted and cleaned proteins from white flakes. They are most often produced by a pH-controlled solubilized extraction, re-precipitation, and neutralization with the intent of removing insoluble fiber. Increasing the pH to 9–11 solubilizes the soy proteins while leaving the fiber undissolved. The fiber is then removed by centrifugation. The white flakes have a total carbohydrate composition of approximately 26%, which is reduced to 5% in the SPI. The protein composition is approximately 90%.[73, 74] Soy protein isolates retail for approximately $4.20/lb, or $8,400/ton.

Soy protein concentrates

Soy protein concentrates (SPC) are prepared by extracting white flakes with an ethanol/water solution. Carbohydrates soluble in the ethanol/water solution are removed and ethanol is recovered from the flakes. The flakes are then dried and sold as SPC. SPC contains 65–67% crude protein.[73] The retail price of soy protein concentrates is $4.50/lb, or $9,000/ton.

Soybean meal

Soybean meal is produced from the solvent-removed and toasted flakes after oil extraction. The flakes are dried, cooled, and ground into the final meal, which is sold as animal feed. Standard specifications for soybean meal are 44% protein, minimum 0.5% fat, maximum 12% moisture, and maximum 7% filter (fiber).[72] Soybean meal is primarily used as poultry feed (56%). Swine, beef, and dairy feed account for 25%, 8%, and 7%, respectively, of its use.[86] Average annual and monthly soybean meal prices are given in **Figure A13**. The average annual price of soybean meal in 2016 was $324/ton.[85]

Soybean hulls

Soybean hulls are used for animal feed and may be mixed with soybean meal depending on final product specifications. Average annual and monthly prices for soybean hulls from 2003 to 2016 are given in **Figure A14**. The average annual price of soybean hulls in 2016 was $113/ton.[85]

Lecithin

The global market for lecithin in 2008 was estimated to be 165,000–187,000 tons/year.[75] Lecithin has a variety of purposes including acting as a wetting and dispersing agent, emulsifier, stabilizer, viscosity reducer, among others. Lecithin is used in several final products such as baking goods, chocolate, margarine, cosmetics, pharmaceuticals, and industrial products such as paints, leather, and textiles.[87] Soy lecithin retails for approximately $1.50/lb, or $3,000/ton.

Soybean carbohydrates

It is desirable to remove the carbohydrates from soybean oil and soybean protein meal, protein concentrates, and other further processed soybean protein products due to lower value and anti-nutritional concerns. These carbohydrates are considered a low-value byproduct or waste, however they have significant potential as substrates for fermentation. Loman et al., recently published a review article describing the potential of using soybean carbohydrates as fermentation feedstocks for production of biofuels, enzymes, and specialty chemicals.[23]

4.6.3 Water, Waste, and Energy

A typical process water treatment is described as follows. Process wastewater from multiple discharge points in the plant flows to a pretreatment sump. The pH of the water in the pretreatment sump is adjusted to between 2 and 3. The water is then pumped through a series of decanter vessels where floatable oils are pumped from the surface and heavier sediment particles are removed from the bottoms of the tanks periodically. After the decanters, the water enters equalization surge tanks where additional sediments can be removed. After the surge tanks the water is neutralized with caustic soda (NaOH) and a cationic-polymer coagulant is added in a pressurized flocculation tank. The water is discharged from the pressurized tank and anionic-polymer coagulant is added before pumping to a dissolved air flotation tank. Any floating material is skimmed from the surface and disposed of as solid sludge waste. The water is then biologically treated with aerobic and/or anaerobic microorganisms in an activated sludge lagoon. The water is clarified, and if it meets final specifications, is discharged to the local sewage system.[88]

National Oilseed Producers Association (NOPA) surveyed 15 soybean processing plants in 2008 and obtained information on water, energy, and waste production.[89] This data is summarized in **Table 15**.

TABLE 15 – Soybean processing data[a] (per 1,000 kg oil produced)

Inputs	
Electricity (kWh)	289
Natural gas (kcal)	1,569,000
Soybeans (kg)	5,236
Hexane (kg)	2.96
Water (kg)	2,547
Outputs	
Soybean meal (kg)	4,131
Soybean oil (kg)	1000
Hexane (kg)	2.96[b]
Water (kg)	1,383[c]
Fats, oil, grease (kg)	<0.14
Nonhazardous solid waste (kg)	8.7

[a] Recreated from NOPA datasheet.[89]

[b] Based on maximum limit of 0.2 gallons of hexane lost/ton of soybeans processed (EPA). Majority lost to evaporation.

[c] Difference between water input and output is primarily due to evaporative losses.

4.7 YEAST AND ENZYME MANUFACTURING

4.7.1 Yeast Production and Processing

Worldwide production of baker's yeast was approximately 3.1 million tons in 2003.[90] It has undoubtedly grown since then. Cedar Rapids currently has one yeast production plant. The average production volume for a typical yeast production plant is approximately 19,000 tons per year.[91] A recent online editorial claims that Red Star Yeast is the largest yeast manufacturing facility in North America, so one may reasonably assume that Red Star Yeast in Cedar Rapids produces greater than 19,000 tons per year of yeast.[92] *Saccharomyces cerevisiae* is the most cultivated yeast and is generally used in brewing, wine-making, and baking. However, other yeasts can be used in specific baking applications where they produce more desirable products than *S. cerevisia*e, as shown in **Table 16**.

4.7.2 Process

Besides the yeast organisms themselves, the primary raw material necessary is the substrate to feed the yeast. Molasses from sugar cane or sugar beets is the generally preferred substrate as yeast preferentially utilizes glucose and fructose over other saccharides. The molasses is washed, centrifuged, and then flash pasteurized to remove microbial contaminants. Other minerals or nutrients are added as needed (N, P, Mg, Ca, trace amounts of Fe, Zn, Cu, Mn, biotin).[93]

TABLE 16 – Yeasts for baking applications[a]

Application	Genus	Species
Multipurpose	*Saccharomyces*	*cerevisiae*
High-sugar doughs	*Saccharomyces* *Saccharomyces*	*rosei* *rouxii*
Favor enhancement	*Saccharomyces*	*delbrukii* *lusitaniae*
Sourdough starters	*Saccharomyces*	*exiguous* *holmii* *milleri*

[a] Table recreated from Poitrenaud[90]

A process flow schematic of the overall yeast production process is shown in **Figure 17**. The first step of the process is propagation, or multiplication, of the yeast cells. This is accomplished in a series of stages where a previous stage produces enough yeast to inoculate the subsequent stage. This is a very controlled process where the physiology and biochemistry of the yeast and liquid medium in each stage is closely monitored. The final inoculation stage is where the yeast for commercial generation is grown. This stage finishes with a maturation phase which stabilizes the yeast and reduces the rate of budding to low levels. Next, the yeast is separated from the wort (liquid phase in which yeast was grown) using centrifugation. The yeast is washed with water and separated to a dry matter concentration of 15–20% creating a cream. Considering the yeast cells contain water, the cream is approximately 50% yeast cells by volume. The cream is cooled to 4°C and stored. It is then filtered and dried and kept cool before distributing for sale. The aqueous phase recovered in the process contains betaine and mineral salts that are concentrated by evaporation and reverse osmosis. It can be used in fertilizer or as an additive to animal feed. The entire batch process begins with less than 0.1 g of yeast and produces approximately 50 tons per tank in the final stage over a period of 10 days.[90] According to Red Star Yeast's website, their plant uses 167 ton tanks in the cultivation stages of the process.

4.7.3 Products

Liquid yeast

Yeast product that is more popular in Australia and the United Kingdom than in North America.[93] Vegemite is an example of a product made from liquid yeast.

Compressed yeast
Most widely used form of yeast that comes in the form of compact blocks to minimize oxygen exposure.

Crumbled yeast
Fine, free-flowing particles of yeast that are sold in sealed plastic packaging. Crumbled yeast is more sensitive to oxygen exposure because of its large surface area.

Rehydratable active dry yeast
Dehydrated form of yeast that is more stable to varying climatic conditions and temperature. The yeast is reconstituted with water rehydrating to approximately five times its dry mass.

Instant dry yeast
Vacuum packed yeast that is stable at room temperature. Instant dry yeast does not need to be rehydrated before being added to flour.

Free-flowing frozen dry yeast
Yeast used in applications such as frozen dough. Frozen dry yeast has a lower moisture content; thus, the yeast membranes remain intact throughout freezing and thawing.

Dry yeast with reducing power
Active dry yeast is a product in the form of small granules that is sold dry for use by pizzerias. Deactivated dry yeast is a product that has no fermenting capacity and is used to improve the machinability of stiff doughs and to accelerate dough development during mixing.

4.7.4 Water, Waste, and Energy

Solid waste produced at typical yeast and enzyme production plants in Cedar Rapids ranges from 600 to 6,000 tons per year. Solid waste is described as consisting of used filter aid media composed of diatomaceous earth, perlite, and carbon, out of specification products, floor sweepings, and broken pallets. Enzyme production plants in Cedar Rapids report liquid waste of 1.5 million gallons per month for a production volume of approximately 7,200 tons of product per month.

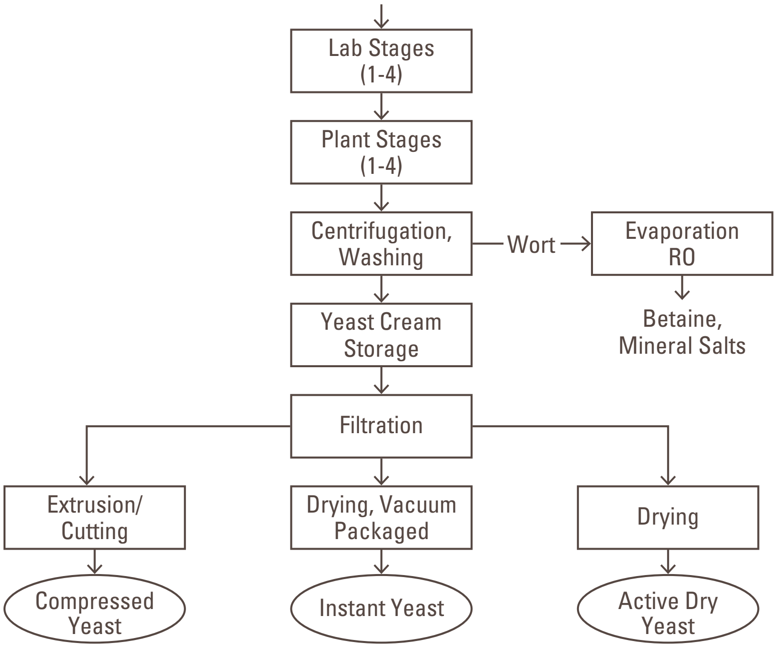

FIGURE 17 – Baker's yeast manufacturing process flow chart.

4.8 PROCESSED FOODS AND PRODUCTS

The processed foods industry in Cedar Rapids encompasses several product manufacturing areas including breakfast cereals, tortillas, bread and bakery products, frozen foods, mayonnaise, dressings and sauces, dried and dehydrated foods, cookies, crackers, and pastas. Each of these product areas has a unique manufacturing process where some process steps may be similar across the product range or they may be completely different from start to finish. There are many food processing operations used by food manufacturers. Examples include size reduction, mixing, separation, irradiation, heat and pressure treatments, blanching, pasteurization, evaporation, sterilization, extrusion, dehydration, smoking, baking, roasting, frying, chilling, freezing, coating, packaging, among others. For the sake of brevity, the following sections will only discuss extrusion, baking and roasting, and packaging as examples of common processing operations. However, many of the other operations may be performed in food processing plants in Cedar Rapids and the interested reader may consult the textbook, *Food Processing Technology,*[94] for thorough evaluations of each of the processing operations mentioned above.

4.8.1 Process

Extrusion

Extrusion is a process that combines mixing, cooking, shaping, and forming to produce food products such as breakfast cereals, pastas, snack foods, and confectionery. Extruders consist of either one or two screws in a horizontal barrel and are classified as either cold extruders or extruder-cookers. Although twin extruders have higher capital, operating, and maintenance expenses, they offer several benefits over single-screw extruders, such as less cleaning needed; the ability to handle viscous, oily, or high sugar materials; and easier operation compared to single screw.[94]

Cold extrusion occurs at temperatures below 100°C and is used to mix and shape foods without cooking them. In extrusion cooking, the food is heated above 100°C through added heat or frictional heat generated in the extruder barrel. The food is subjected to increased pressure and shearing and is forced through the barrel and out of a restricted opening (die). As the food exits the die, it rapidly cools and expands to its final shape. Since the water in the food was under elevated pressure in the extruder, it immediately evaporates upon being exposed to atmospheric pressure as it exits the die. A variety of shapes are possible including rods, spheres, doughnuts, tubes, strips, swirls, and shells. The extruded products can be further processed by cutting, drying, frying, coating, or other relevant food processing steps. Extrusion is a popular process as it can produce a variety of products and shapes that are not easily produced by other methods and is generally lower in costs than other methods. Extrusion itself does not produce any effluents or create any water treatment costs.[94] Heat and the energy to mechanically operate the extruder are the major inputs to this process. Single-screw extruders use 0.10–0.16 kWh/kg for high shearing operation and 0.01–0.04 kWh/kg for low shearing operation with kg indicating mass of processed product. Using extrusion for breakfast cereal manufacture has reduced material costs 20%, energy consumption 90%, and capital expenditure 44% compared to the process of cooking, drying, tempering, flaking, and toasting corn grits to make cereals.

Baking

Baking and roasting are food processes with which most people are generally familiar. They are similar processes where baking is usually used to describe the process for flour-based foods and fruits, and roasting refers to that for meats, cocoa, coffee beans, nuts, and vegetables. Baking is a process that involves transfer of heat into food and removal of moisture by evaporation from the food. Baking is usually performed at higher temperatures than dehydration processes.

The goals of baking can be different depending on the food. For example, with some foods such as cakes, breads, and meats, it is desired to induce changes at the surface of the food and retain moisture in the center of the product. In other products such as biscuits and crisps, the intention is to dry the interior of the food to obtain the desired crispness. Therefore, heat can serve a variety of functions, including: destroying microorganisms, evaporating water, forming crusts, and superheating water vapor that then leaves the interior of the product. The three modes of heat transfer typically used are infrared radiation, convection, and conduction.[94]

The physical phenomena of baking reduce to topics of heat and mass transfer that can be controlled by several methods. For example, there exists a boundary layer of stagnant air surrounding the food product that heat and moisture must travel through during the process. In convective heating, the boundary layer thickness can be reduced by using moving air which increases heat transfer and moisture removal. Since moisture exits the food product at its surface, larger products will require longer baking times to remove moisture, for example, bread compared to crackers. Crust formation is an important phenomenon for some foods, which is caused by rapid heating that can lead to physical, chemical, or morphological changes at the surface. The crust serves as an insulating barrier to heat transfer into the product and moisture transfer out of the product.

Packaging

Packaging is a process ubiquitous to most food processing plants. The purpose of packaging is to contain and protect food from microorganisms, contaminant exposure, oxygen intrusion, moisture movement into or out of the food, and other hazards that may be encountered.[94] Packaging should also be inert in contact with the food product and not influence the selection or proliferation of microorganisms naturally present in the food product. Packaging materials may be composed of polymer, glass, metal, or some composite material. Important characteristics of packaging materials include permeability to moisture and gases, light transmission or reflectance, reusability, sealing quality, mechanical durability and strength, antimicrobial behavior, interaction with the food product, and cost, among others. One might imagine there are a number of product-specific factors that must be considered when packaging food depending on the type of food, shelf-life, moisture content, etc.

4.8.2 Products

Several types of finished processed food products are manufactured in Cedar Rapids. Major categories include RTE breakfast cereals, extruded and sheeted snacks, soup products, and general food ingredients.

4.8.3 Water, Waste, and Energy

Water use in processed food manufacturing depends on the food product and unit operations performed. Steam may be used in a specific operation like extrusion to assist in hydrating or sterilizing the material to be extruded. Water may be added to specific products such as soups, dressings, doughs, batters, etc. Water and/or steam may be used for cleaning equipment. Steam may be used for heating operations.

Energy use will depend on the specific unit operations performed in a plant; however, one might surmise that baking, evaporating, dehydrating, cooking, extrusion, sterilizing, and many other operations all use an amount of energy proportional to the amount of water that evaporates, the temperature of the process, the volumes processed, the size of the heaters/ovens, and duration if it is a batch process.

5. Conclusions

The City of Cedar Rapids has a long and significant history of grain processing and bioproduct manufacturing. The facilities and plants in Cedar Rapids generate approximately $4.8 billion in revenue annually. According to current labor market analysis, as of 2017 the manufacturing industry in Cedar Rapids employs 20,080 individuals where 3,965 and 756 are in areas of food and chemical manufacturing, respectively. There are several dozen companies and plants in Cedar Rapids that produce a variety of primary products including ethanol, grain-based food products, animal feeds, yeasts, processed foods, vegetable oil, among others. Alongside the major primary products, there are lesser valued secondary products and significant solid and liquid waste streams. Technological advances and developments over the past few decades have introduced novel avenues for converting these lower value and waste streams to higher valued products. Examples of potential technologies on the horizon include acid hydrolysis of distillers wet grains to produce xylose, recovery of phytic acid from thin stillage in a dry-grind facility, conversion of oat hulls to furfural or for use directly as a solid fuel, fermenting corn steep liquid to valuable bioproducts, and hydrogenating vegetable oils with novel catalytic and more efficient methods to produce less trans fats. This report has provided an overview of the major grain processing and biobased manufacturing activities in Cedar Rapids in an effort to identify where novel and emerging technologies could be employed to enhance current facilities or allow new companies to start up and grow in Cedar Rapids.

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Appendix

A.1 CORN PRODUCTS HISTORICAL PRICES

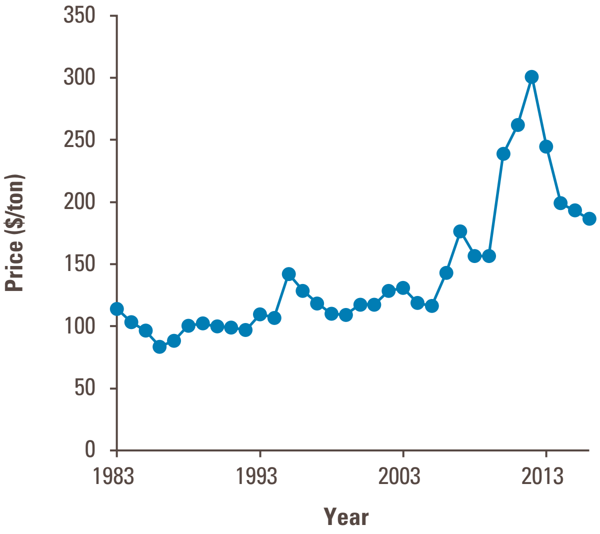

FIGURE A1 – Brewer's grits price in the Midwest.[5]

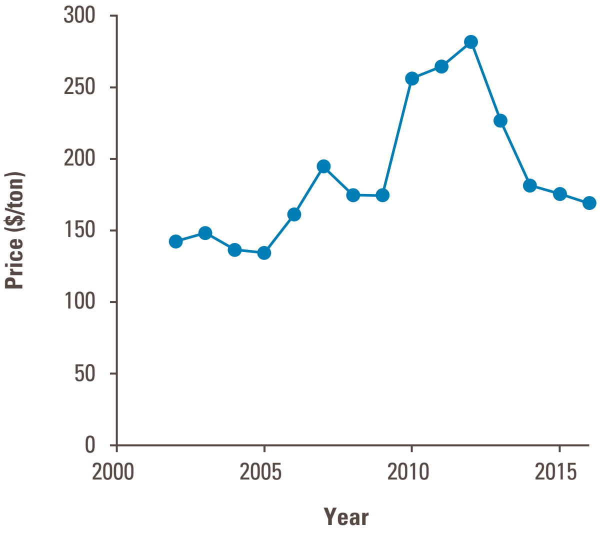

FIGURE A2 – Cornmeal price in Chicago (USDA).[5]

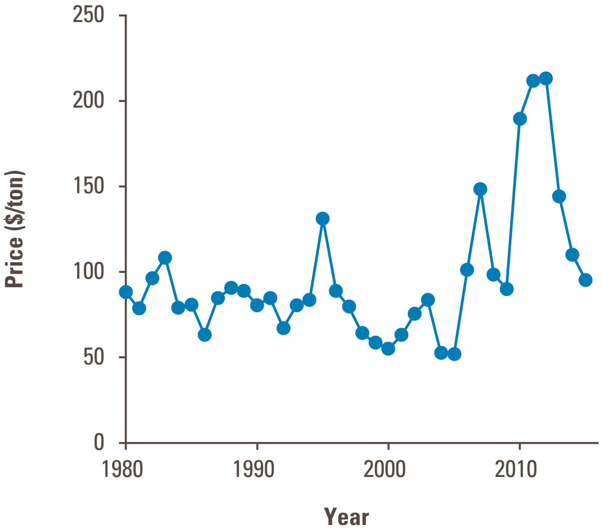

FIGURE A3 – Hominy feed price in Illinois.[5]

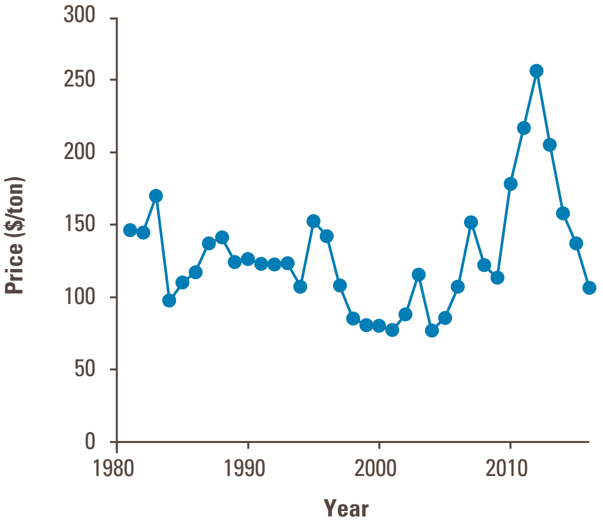

FIGURE A4 – Average annual DDGS price (October–September).[95]

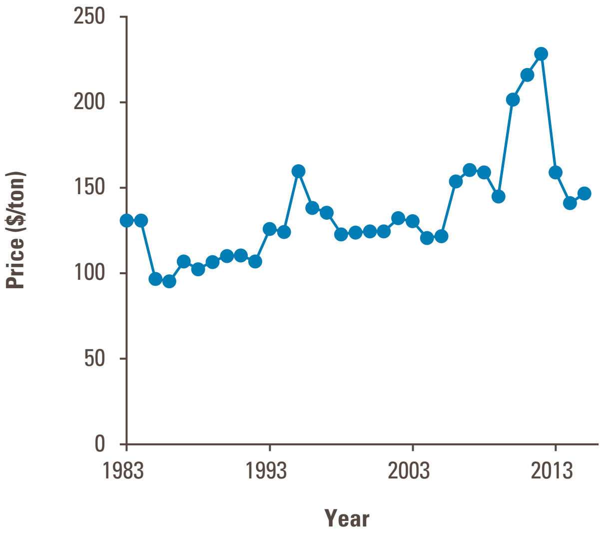

FIGURE A5 – Unrefined corn starch price in the Midwest.[5]

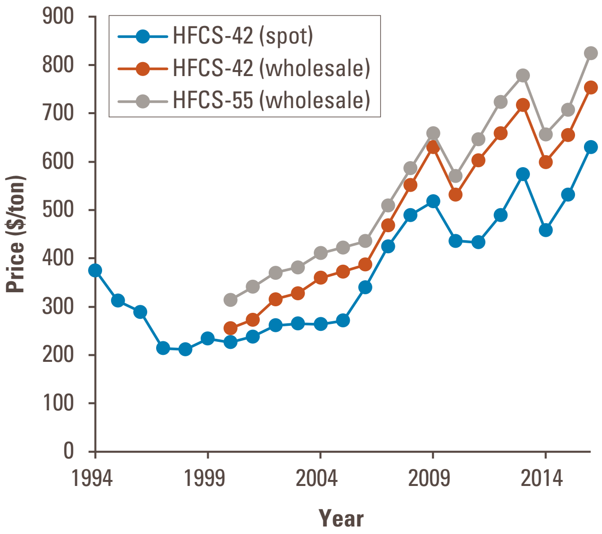

FIGURE A6 – HFCS spot and wholesale prices on a dry basis. (Multiply HFCS-42 by 0.71 and HFCS-55 by 0.77 for wet basis).[56]

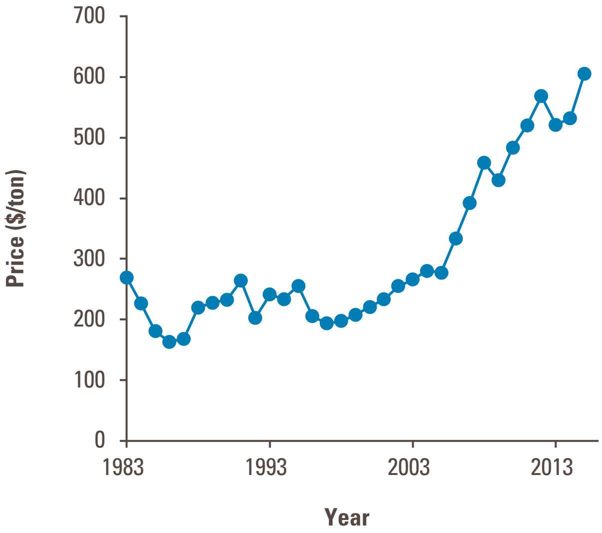

FIGURE A7 – Corn syrup price in the Midwest.[5]

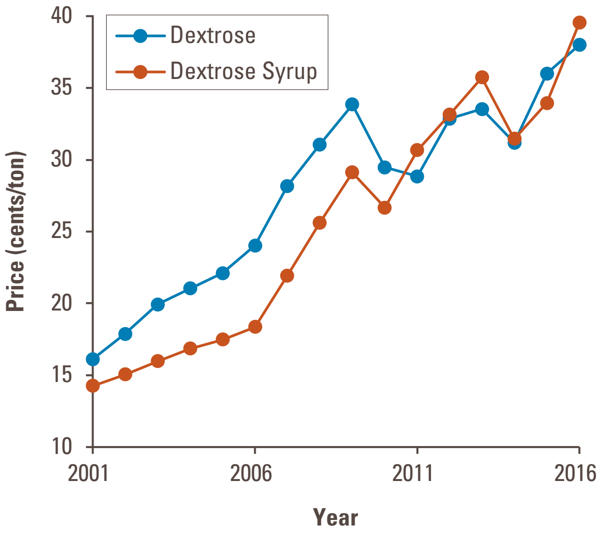

FIGURE A8 – Dextrose wholesale list price on a dry basis.[56]

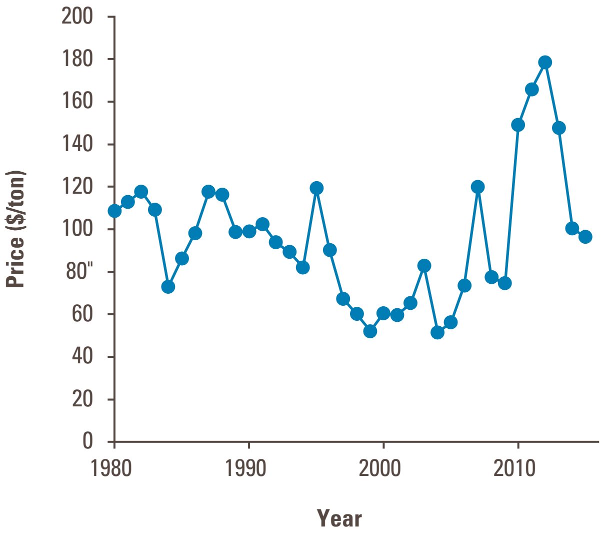

FIGURE A9 – Corn gluten feed price in the Midwest.[5]

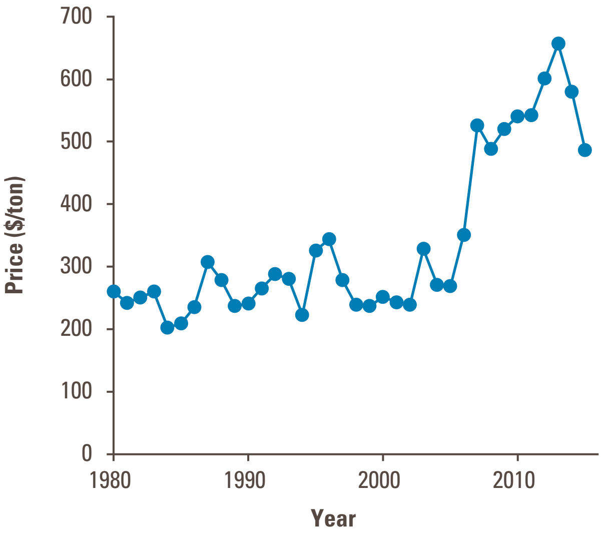

FIGURE A10 – Corn gluten meal price in the Midwest.[5]

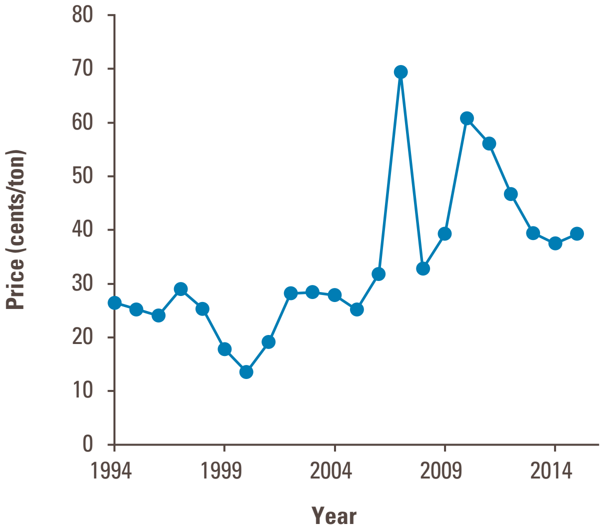

FIGURE A11 – Corn oil price in the United States (years begin in October).[58]

A.2 SOYBEAN PRODUCTS HISTORICAL PRICES

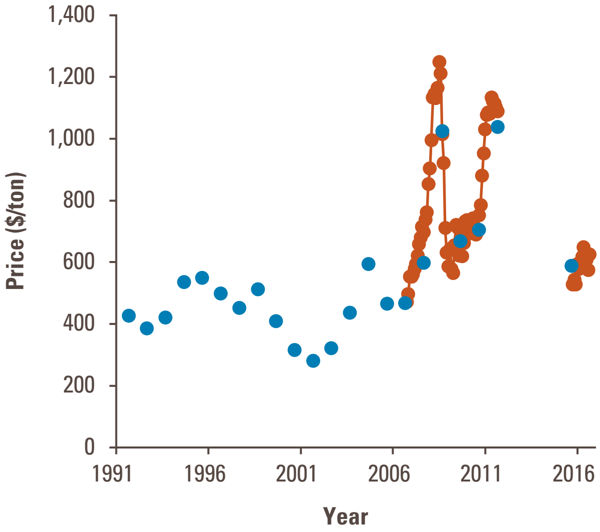

FIGURE A12 – Soybean oil price in central Illinois. Blue circles are annual averages and orange symbols are monthly averages. Data from September 2011 to August 2015 not available.[85]

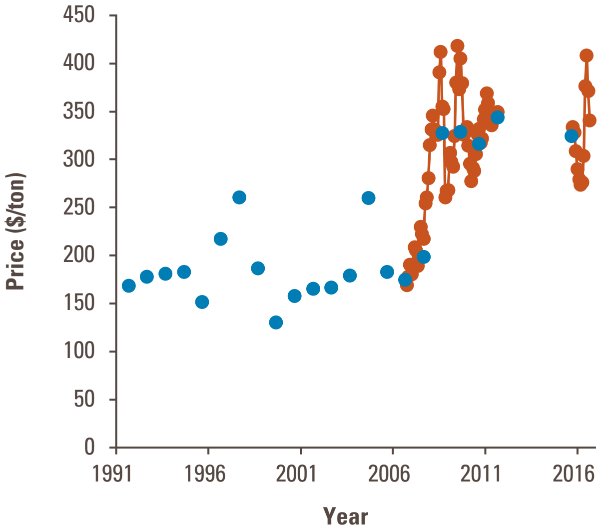

FIGURE A13 – Soybean meal price in central Illinois. Blue circles are annual averages and orange symbols are monthly averages. Data from September 2011 to August 2015 not available.[85]

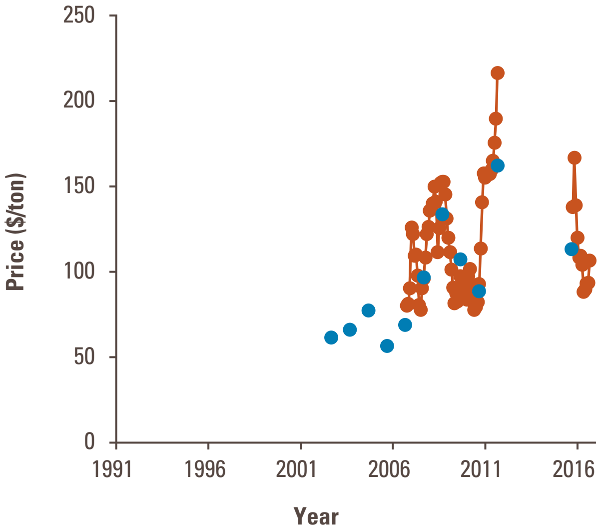

FIGURE A14 – Soybean hulls price in central Illinois. Blue circles are annual averages and orange symbols are monthly averages. Data from September 2011 to August 2015 not available.[85]

A.3 CEDAR RAPIDS WASTEWATER TREATMENT PLANT DATA

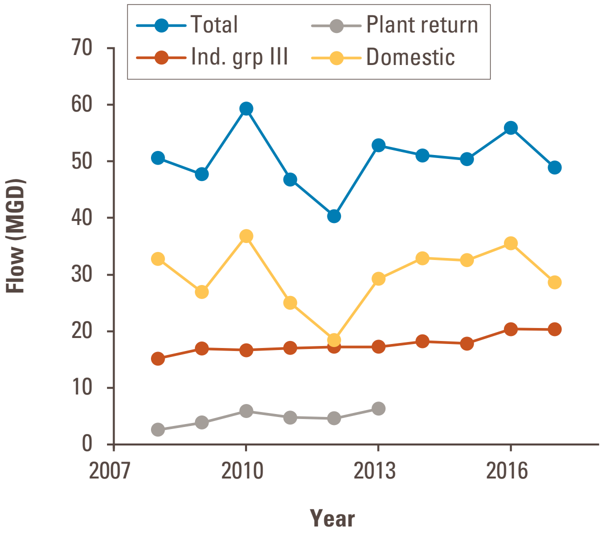

FIGURE A15 – Cedar Rapids wastewater treatment plant flow data.

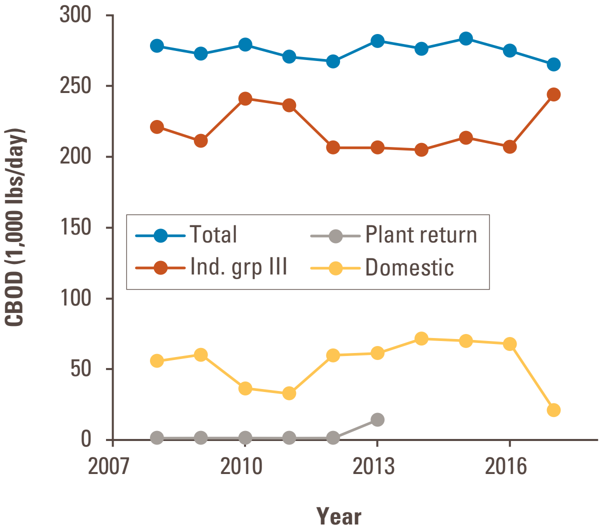

FIGURE A16 – Carbonaceous biochemical oxygen demand (CBOD) values for Cedar Rapids wastewater treatment plant.

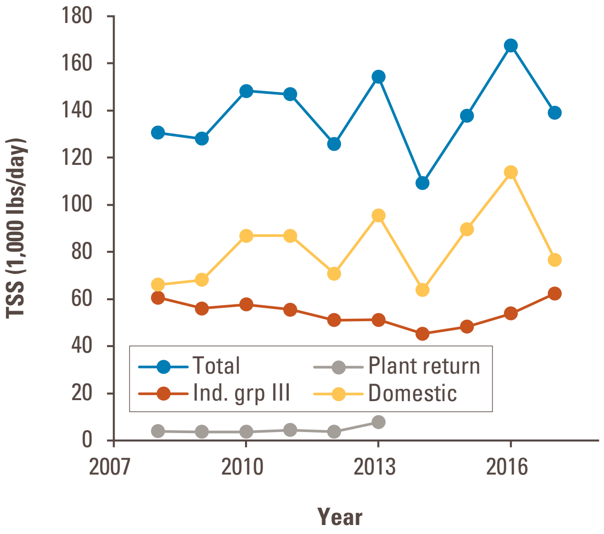

FIGURE A17 – Total suspended solids (TSS) values for Cedar Rapids wastewater treatment plant.

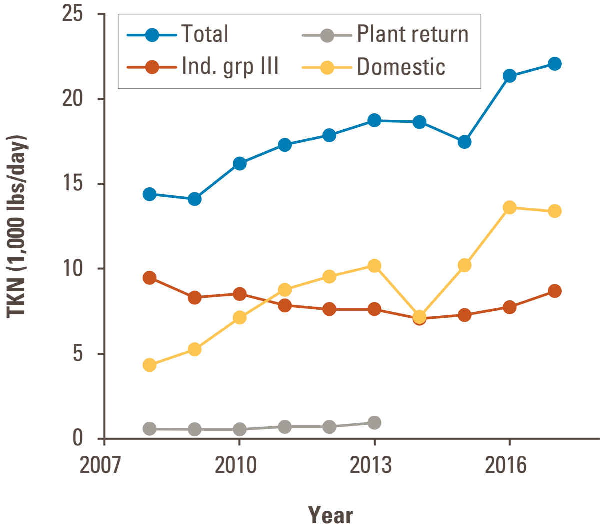

FIGURE A18 – Total Kjeldahl nitrogen (TKN) values for Cedar Rapids wastewater treatment plant.

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