



IOWA STATE
UNIVERSITY

CEDAR RAPIDS FOOD AND BIOPROCESSORS MANUFACTURING REPORT

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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, oat, and soybean raw materials processed in Cedar Rapids is valued at roughly \$2 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 4,000 individuals in manufacturing

activities, and median income for cluster employment is 43% higher than the citywide average. For the period between 2010 and 2023, employment in the food and bioprocessing cluster increased at a rate nine times that found in the general employment in the Cedar Rapids area. Given just the corn and soybean processing in the city, it takes roughly 2.1 million acres of Iowa farmland to produce the raw ingredients needed for the ag processing sector in 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.

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1. List of Terms

Amylopectin

Highly branched polysaccharide composed of glucose units with linearly connected $\alpha(1-4)$ bonds and branched $\alpha(1-6)$ 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 $\alpha(1-4)$ 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 $\alpha(1-4)$ 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 136,000 residents. Regionally, there are nearly 800,000 workers within an hour's drive of Cedar Rapids.¹ Nearly 15% of employed individuals in Cedar Rapids work in areas of manufacturing and agriculture.² 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. For the period between 2020 to 2025, economic forecasts show employment in the food and biomanufacturing cluster is growing at a rate seven times greater than overall manufacturing employment in Cedar Rapids.³ Average annual wages in Cedar Rapids over the same period were \$61,653, while the food and bioprocessing cluster average annual wages was \$87,922.³ Earnings for firms per job in the food and bioprocessing cluster was \$109,341, compared to the average value of \$75,334.³ Nominal gross domestic product of the food and biomanufacturing sector in Cedar Rapids exceeded \$1.48 billion in 2022.³ 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 lb. (907 kg). Occasionally the text refers to “metric tons” meaning 1,000 kg (2,205 lb.). 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 as 56.00 lb. with a moisture content of 15.5%. A bushel of oats is defined as 32 lb. with 14% moisture. A bushel of soybeans is defined as 60 lb. 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 2022 totaled 13.7 billion bushels.⁴ 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%).^{5,6} These values are consistent with those given by Watson and reproduced in **Table 3**.⁷ 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.^{6,8} 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.⁸

TABLE 1 – USDA grades and grade requirements for corn*

Grade	Minimum test weight per bushel (lb.)	Maximum limits of:		
		Damaged kernels		Broken corn and foreign material (%)
		Heat damaged kernels (%)	Total (%)	
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 corn: (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% 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% 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 USDA AMS.⁹

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).¹⁰ A more detailed compositional analysis of yellow dent corn is given in **Table 2**.⁷ 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.⁷

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.⁷ 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%.

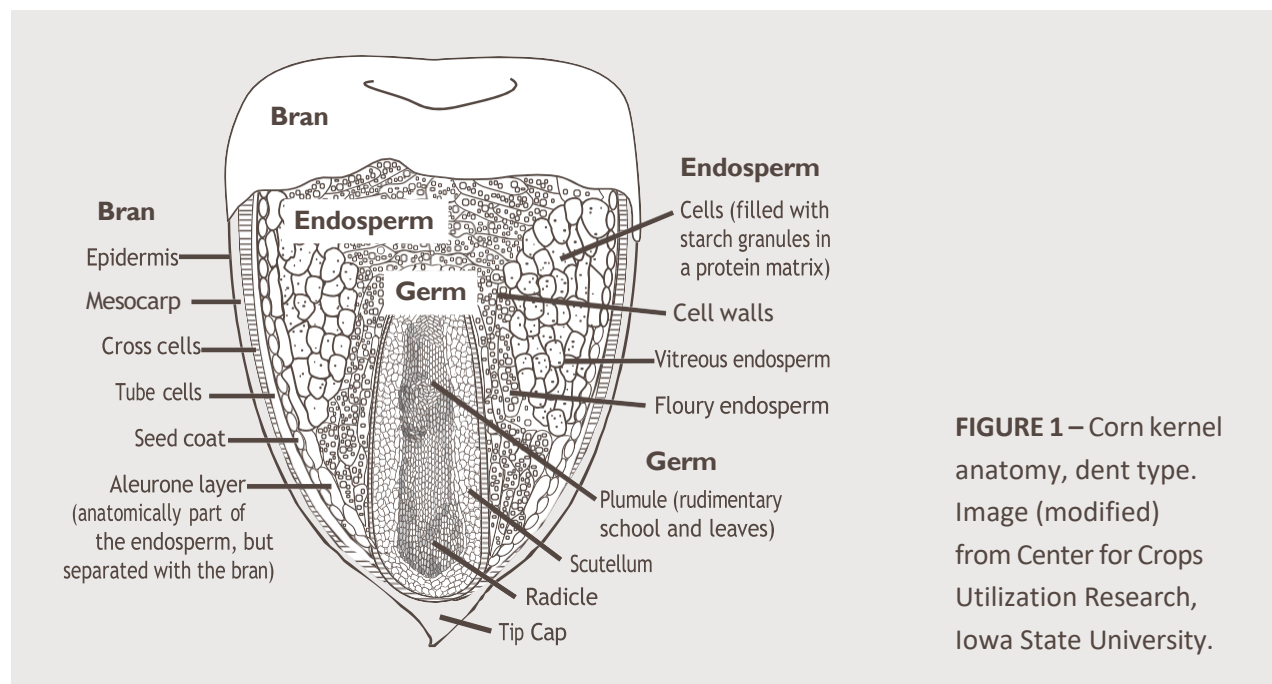


FIGURE 1 – Corn kernel anatomy, dent type. Image (modified) from Center for Crops Utilization Research, Iowa State University.

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

Part	% dry weight of whole kernel	Composition of kernel parts (% dwb) ^b				
		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.⁷

^b % dry weight basis.

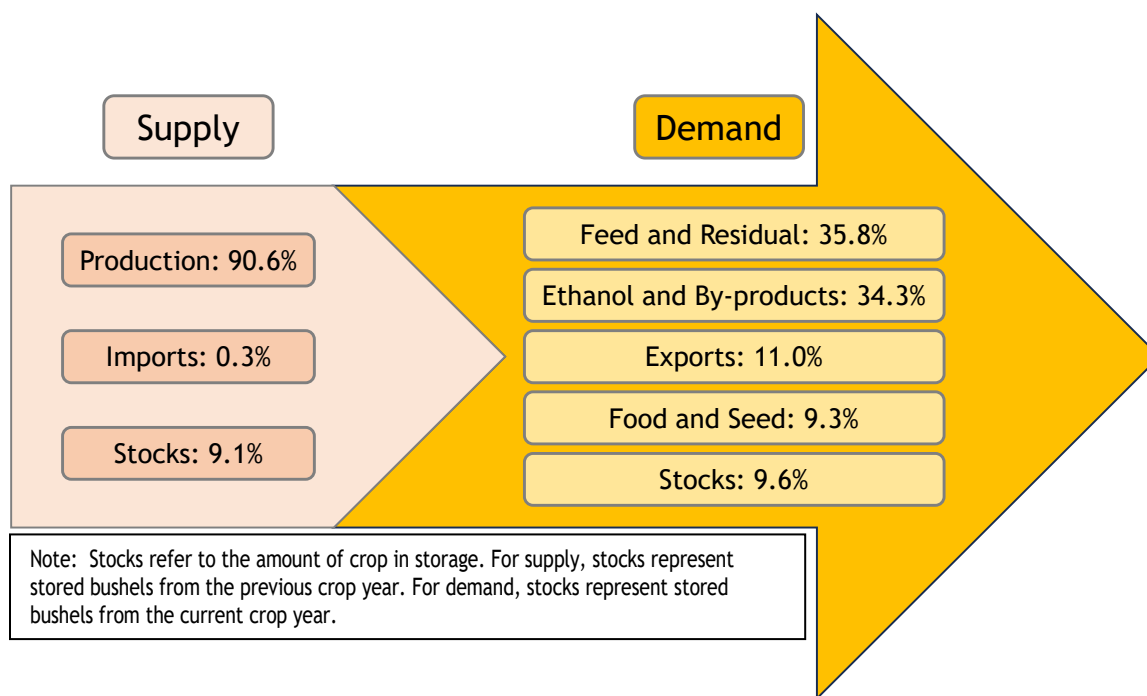


FIGURE 2 – Typical corn supply and usage, based on 2022 data.¹¹

In 2022, the United States produced 13.730 billion bushels of corn, had 1.377 billion bushels in storage (referred to as stocks, shorthand for crop stocks) at the beginning of the marketing year, and imported 39 million bushels, for a total of 15.13 billion bushels of corn available throughout the marketing year.¹¹ There are four main uses of corn: livestock feed, ethanol production, exports, and food, seed, and other industrial uses (mainly for corn sweeteners). Figure 2 shows the typical usage pattern for U.S. corn.

Iowa corn producers created 2.48 billion bushels of corn in 2022, from 12.9 million acres devoted to the crop.¹² Iowa is the top ranked state in corn production, with roughly 18% of total U.S. production. In the eight-county (Benton, Buchanan, Cedar, Delaware, Iowa, Johnson, Jones, and Lynn) region surrounding Cedar Rapids, farmers planted nearly 1.2 million acres to corn, producing 251 million bushels.¹² This represents 10% of Iowa’s corn production and 1.8% of the nation’s total.

3.2 OATS

Oats are one of the world’s significant cereal crops, ranking as the seventh-largest grain crop by production in 2022.¹³ Since 2007, global oat production has averaged 23.1 million tons per year.^{14,15} In 2022, global oat production exceeded 25 million tons.¹³ In 2007, the United States produced over 1.3 million tons of oats.¹³ By 2022, U.S. oat production had fallen to 837,000 tons.¹³ The United States has become predominately an importer of oats with roughly 1.5 million tons of oats per year coming from other countries. While oat usage has slowly declined over time, the United States will directly use or further process approximately 2 million tons of oats in 2022.

Worldwide oat production has 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, since 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

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*.¹⁴ Values presented represent averages.

cattle and as cover crops during crop rotations.¹⁵

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 3**. 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.^{6,14}

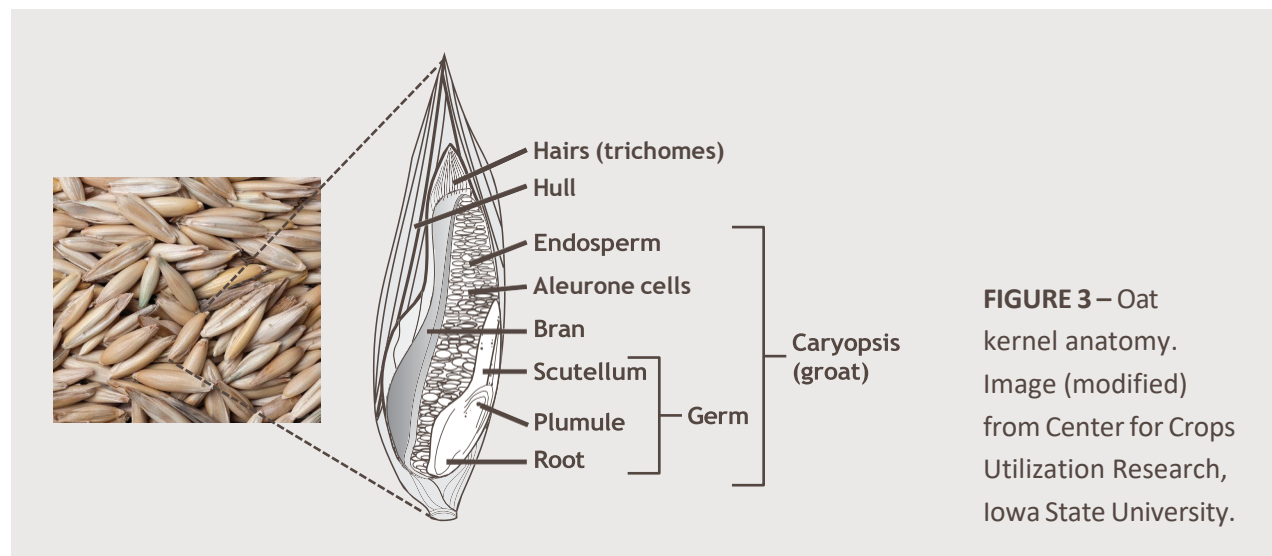


FIGURE 3 – Oat kernel anatomy. Image (modified) from Center for Crops Utilization Research, Iowa State University.

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.¹⁴ 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. Starch is mainly stored in the endosperm and consists of irregularly shaped clustered granules that vary from 3 to 10 μ m 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.¹⁴

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.¹⁶

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.¹⁷

When compared to other cereal grains, oats have a relatively higher lipid content ranging from 3.1-11.8%. 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.¹⁸

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.¹⁹

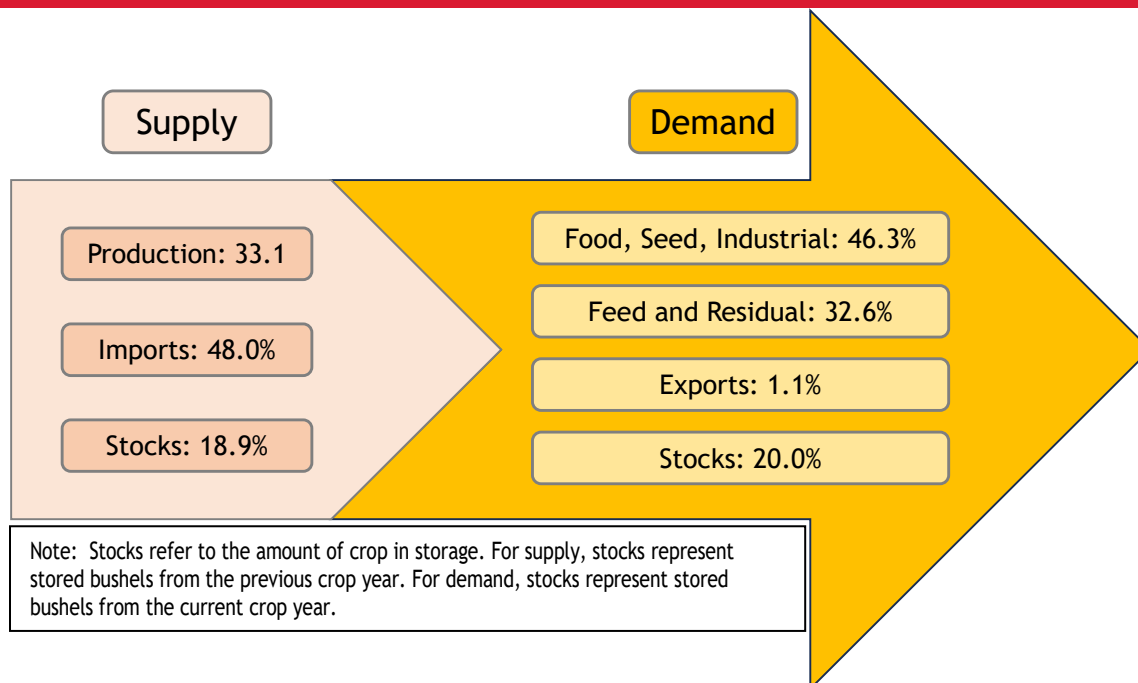


FIGURE 4– Typical oat supply and usage, based on 2022 data.¹¹

In 2022, the United States produced 58 million bushels of oats, had 33 million bushels in storage (stocks) at the beginning of the marketing year, and imported 84 million bushels, for a total of 174 million bushels of oats available throughout the marketing year.¹¹ There are two main uses of oats: livestock feed and food, seed, and other industrial uses. Figure 4 shows the typical usage pattern for U.S. oats.

Iowa oat producers planted 130,000 acres in 2022, raising 3.2 million bushels of oats.¹² Iowa is the sixth-largest state in oat production, with roughly 5% of total U.S. production. In the eight-county (Benton, Buchanan, Cedar, Delaware, Iowa, Johnson, Jones, and Lynn) region surrounding Cedar Rapids, farmers planted 9,400 acres to oats, producing 3.2 million bushels.¹² This represents 8% of Iowa's oat production and 0.4% of the nation's total.

3.3 SOYBEANS

Soybeans are a dominant oilseed in the United States and worldwide. In 2022, the United States produced nearly 4.3 billion bushels, or 116 million metric tons of soybeans.²⁰ This amounts to approximately one-third of total worldwide production for 2022, which was 370 million metric tons.²¹ In 2022, Iowa produced 586 million bushels or 16 million metric tons of soybeans, which is 4.3% of total worldwide production.²²

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 5. 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.²³

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 6. The

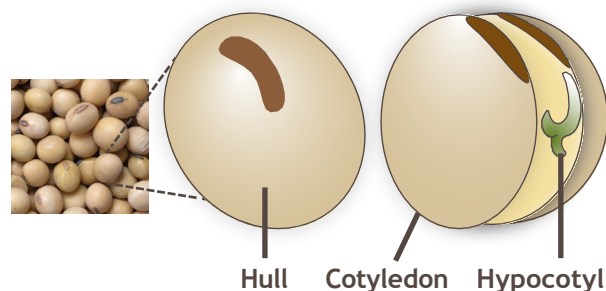


FIGURE 5 – Soybeans and main soybean components. Photograph on left from Center for Crops Utilization Research, Iowa State University.

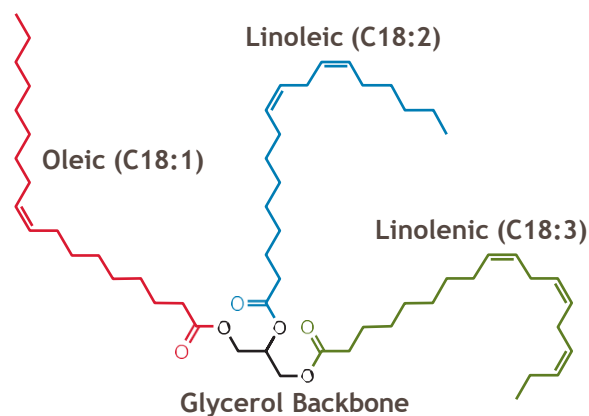


FIGURE 6 – Triglyceride structure with three unsaturated fatty acid chains. Oleic acid (red), linoleic acid (blue), linolenic acid (green). All double bonds are in the cis configuration.

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*.²⁴

^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 6 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 6 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.

In 2022, the United States produced 4.27 billion bushels of soybeans, had 274 million bushels in storage (stocks) at the beginning of the marketing year, and imported 25 million bushels, for a total of 4.569 billion bushels of soybeans available throughout the marketing year.¹¹ There are two main uses of soybeans: domestic crush (to create soybean meal and oil) and exports. Figure 7 shows the typical usage pattern for U.S. soybeans. Figures 8 and 9 show the supply and usage patterns for soybean oil and meal. In 2022, the United States had total supplies of 28.631 billion pounds of soybean oil and 53.5 million tons of soybean meal.

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.²⁴

Iowa farmers planted 10.1 million acres to soybeans in 2022, raising 587 million bushels of soybeans.¹² Iowa is the second-largest state in soybean production, with roughly 14% of total U.S. production. In the eight-county (Benton, Buchanan, Cedar, Delaware, Iowa, Johnson, Jones, and Lynn) region surrounding Cedar Rapids, farmers planted 822,600 acres to soybeans, producing nearly 53 million bushels.¹² This represents 9% of Iowa's soybean production and 1.2% of the nation's total.

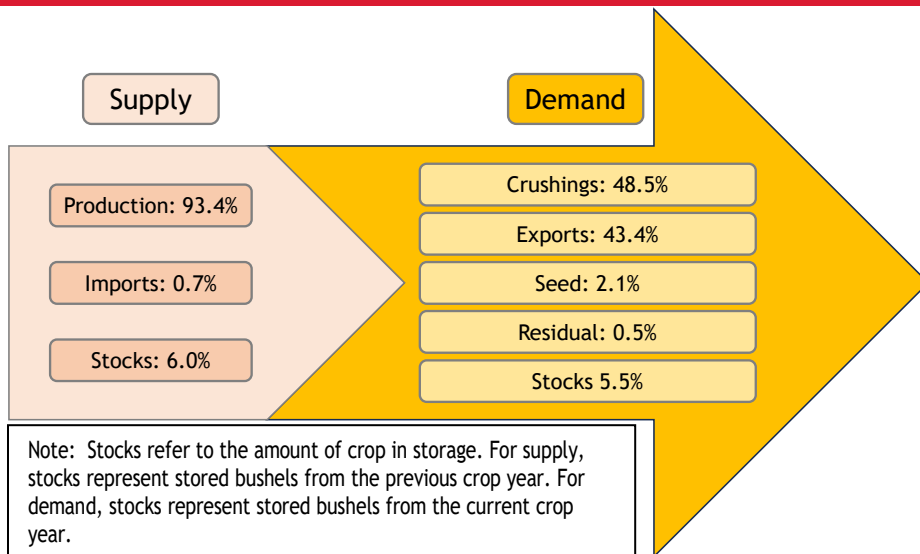


FIGURE 7 – Typical soybean supply and usage, based on 2022 data.¹¹

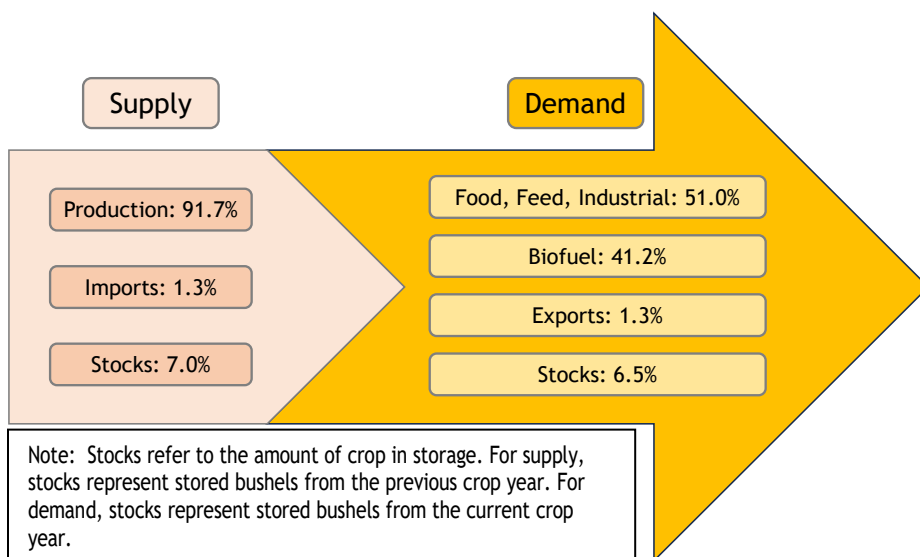


FIGURE 8 – Typical soybean oil supply and usage, based on 2022 data.¹¹

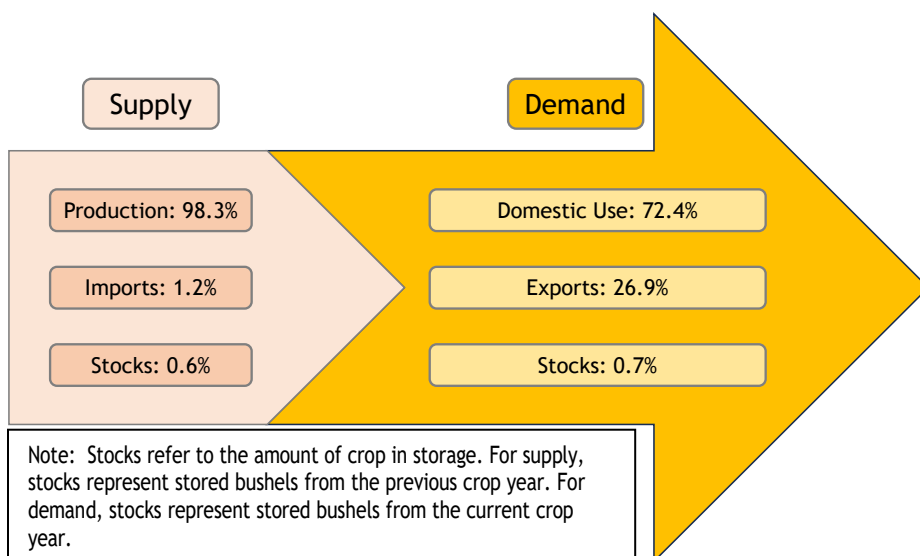


FIGURE 9 – Typical soybean meal supply and usage, based on 2022 data.¹¹

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, thus 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.²⁶ 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.²⁷ 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 with approximately 80% of current ethanol coming from dry-grind facilities and 20% from wet milling facilities. The 2022 production capacity of Iowa is given by the Renewable Fuels Association as 4.5 billion gallons of ethanol produced by 42 currently operating ethanol biorefineries.²⁸ Total U.S. ethanol production in 2022 was 15.4 billion gallons, meaning Iowa accounted for over one-fourth of the total

national production of ethanol.²⁹

It is estimated that the corn processors in Cedar Rapids in 2022 processed nearly 300 million bushels of corn between dry grinding and wet milling. As the eight-county region around Cedar Rapids produces roughly 250 million bushels, this implies that Cedar Rapids corn processing draws corn from well beyond surrounding counties. Given Iowa's average corn yield of 200 bushels per acre in 2022, it takes 1.5 million acres of Iowa farmland to fulfill Cedar Rapids' corn processing needs.

While the national scene is dominated by dry milling, consuming 82.5% of all milled corn, Cedar Rapids corn processing is more evenly split. In 2022, corn processing in Cedar Rapids accounted for approximately 5% of total U.S. annual corn processing, which was 5.843 billion bushels.³⁰

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 2017 total city usage is 17.8 billion gallons per year according to the 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.³¹ The typical corn dry milling process is shown in **Figure 10**.

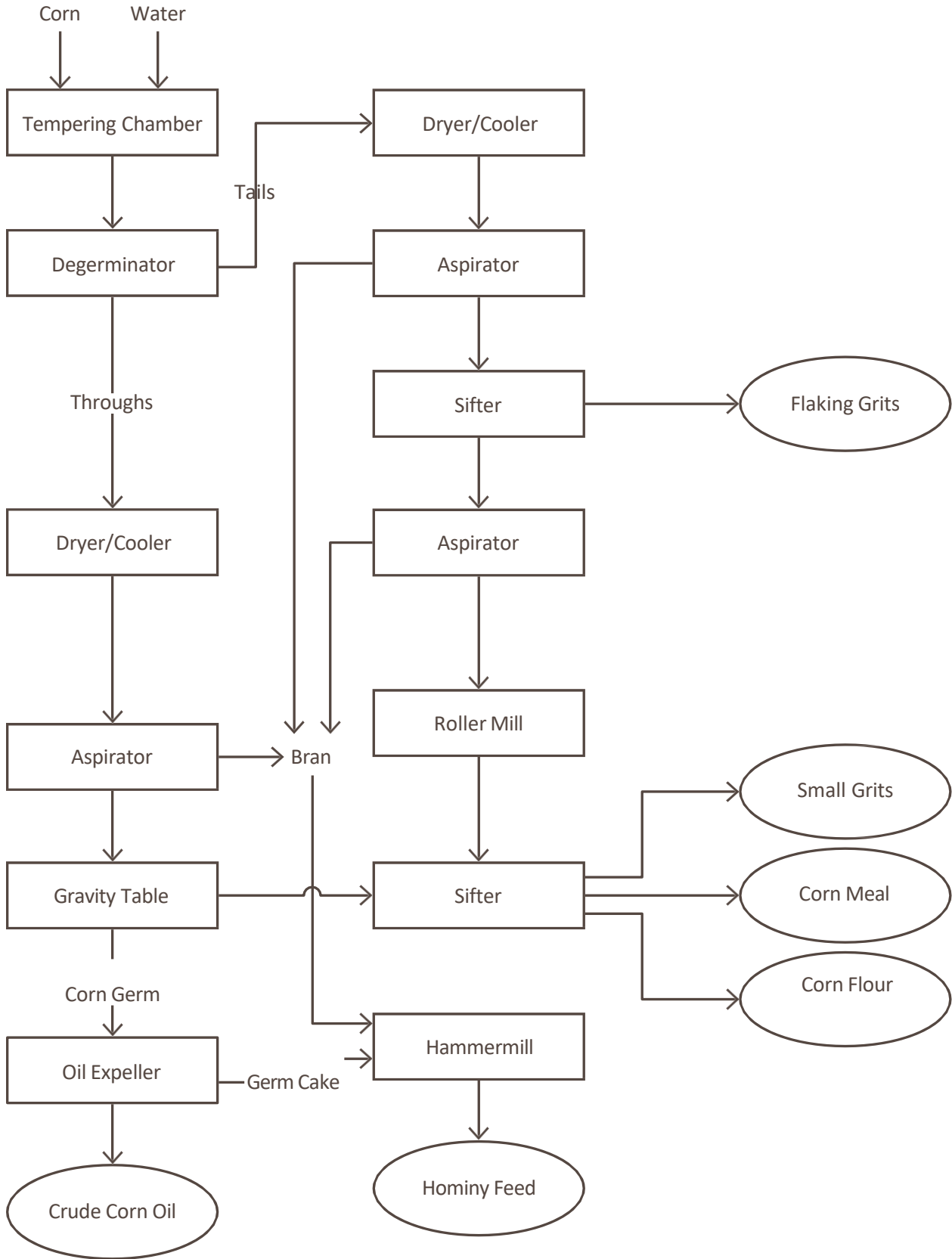


FIGURE 10– Corn dry milling process. Adapted from Rausch et al.²⁶

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 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.³¹ 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, thus 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%.³¹ 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.³¹

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.³¹

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**.³¹

TABLE 8 – Dry milling product yields

Product	Yield	
	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.²⁶

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.³¹

Flaking grits

Flaking grits are the largest pieces of broken corn endosperm, formed from corn that is crushed and peeled before the hull, germ, and coarse meal are separated. Flaking grits are used in breakfast cereals, brewing, tortillas, flour, and snack products. USDA does not gather pricing information for flaking grits.

Brewer's grits

Brewer's grits are smaller endosperm particles compared to flaking grits and are mainly used for breweries. The Midwest price of brewer's grits was \$567.30 per ton in June 2023, according to the USDA's feed grains database.³² The 10-month average price from September 2022 to June 2023 increased by 12.7% from a year earlier. **Figure A1** gives the price of brewer's grits in the Midwest from 1983 to 2023 according to the USDA.³²

Cornmeal

Cornmeal is made by milling dried corn to a coarsely ground texture and can be used in baking and other corn-based products. The Midwest price of cornmeal was \$531.90 per ton in June 2023, according to the USDA's feed grains database.³² The 10-month average price from September 2022 to June 2023 increased by 13.5% from a year earlier. **Figure A2** gives the price of cornmeal from 2002 to 2023.³²

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. The U.S. retail prices of corn flour are about \$280-\$360 per ton, and the wholesale prices ranged between \$200-\$260 per ton in 2023.³³

Hominy feed

Hominy feed is a dry and ground mixture of germ cake, pericarp (bran), and standard meal (endosperm that is usually high in oil, fine fiber, and tip caps). It is widely used for dairy, swine, feeder cattle, and aquatic feed mixes as a high-energy replacement for whole corn. The Midwest price of hominy feed was \$183.25 per ton in June 2023, according to the USDA's feed grains database.³² The 10-month average price from September 2022 to June 2023 increased by 20.6% from a year earlier. **Figure A3** gives the price of hominy feed in Illinois from 1980 to 2023.³²

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 11. 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.²⁹ 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 20 years. In 2002, 50% of U.S. ethanol plants were dry grind. By 2009, the fraction had increased to over 80% of all facilities.³⁴ In 2022, 92.6% of ethanol production came from dry mills.²⁹ In general, one bushel of corn (56 lb.) will yield 2.9 gallons of ethanol, 15.1 lb. of distillers grains, 0.9 lb. of corn oil, and 16 lb. of carbon dioxide (CO₂).²⁹

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.^{34,35} Particle size does have an effect on the amount of ethanol produced by fermentation and the amount of dissolved solids in the thin stillage.³⁶

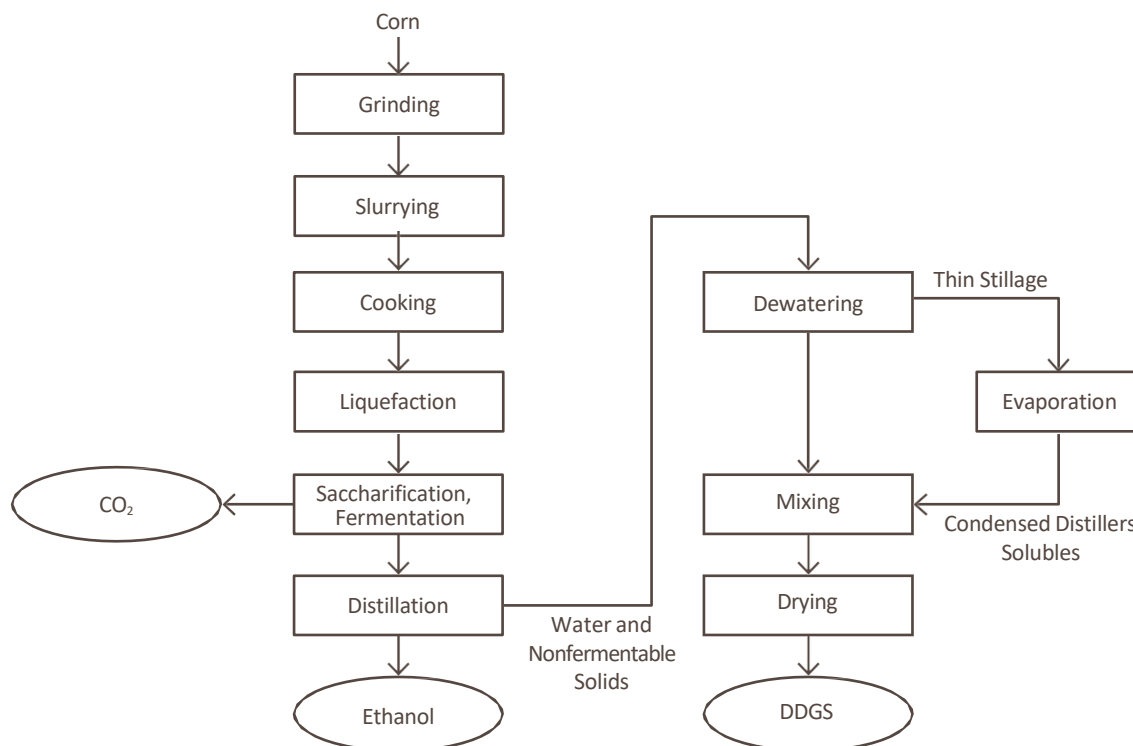


FIGURE 11 – Dry-grind process for producing ethanol and DDGS. Recreated from Liu.³⁴

The next process steps are slurring, 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.³⁴

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 greater than 528,000 gallons (2 million liters) in volume.^{37,38} 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, CO₂, and distillers grains. The CO₂ produced can be cleaned, compressed, and sold, but often logistics and economics prohibit this option, so plants usually scrub the CO₂ and release it to the atmosphere.³⁴

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.³⁴ 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 wet distillers grains (WDG). The thin stillage is evaporated to produce condensed distillers solubles. These solubles are then combined with WDG and dried to approximately 10-12% moisture on a wet basis producing DDGS.

4.3.2 Products

Ethanol

Ethanol is the main output from dry-grind technology. Dry mills account for almost 90% of U.S. grain ethanol plants and over 92% of U.S. ethanol production due to lower capital costs, while the remaining facilities are wet milling.^{29,39} Based on Renewables Fuels Association data, Iowa is the largest ethanol producer in the United States, with over 40 ethanol plants and a production capacity of 4.8 billion gallons per year, or 27.3% of the U.S. total capacity, as of January 1, 2023.⁴⁰ Cedar Rapids is the home of two ethanol plants owned by ADM, the names and capacities of these plants is given in **Table 10**. The average per-gallon ethanol price in 2022 was \$2.61.⁴¹ If both ethanol production plants in Cedar Rapids operated at full capacity, it would generate approximately \$1.4 billion in gross revenue from ethanol.

Figure 12 gives the rack price of ethanol per gallon from 1982 to present (FOB Omaha).⁴¹ Cedar Rapids, Iowa, has two ethanol production plants listed by the Renewable Fuels Association for 2023.

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.

DDGS are a major co-product of dry-grind ethanol production. They are mainly used as a high-protein animal feed, especially feeding cattle, dairy cows, swine, and some poultry. In 2021, U.S. total DDGS production reached 36.1 million metric tons, of which 11.4 metric tons were exported.⁴² DDGS are usually dried to contain about 10-12% moisture, which can reduce weight, avoid spoilage, and be easily stored and transported. More than 10 million metric tons of DDGS have been exported annually since 2014.

Some dry-grind plants sell WDG, although to a much lesser extent than DDGS. Distillers grains (DDGS and WDG) often contribute between 10-20% of a plant’s total revenue and sometimes can reach as high as 40% depending on market conditions.³⁴ This point is illustrated in **Figure 13**, which shows the proportion of value of a bushel of corn that is generated from DDGS production in the dry-grind process.⁴³ Note that Figure 13 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

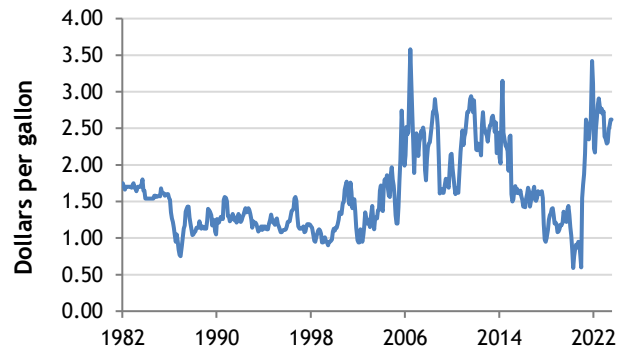


FIGURE 12 – Ethanol rack price per gallon (FOB Omaha).

TABLE 10 – Cedar Rapids, Iowa, ethanol production in 2013²⁹

Company	Production capacity (mg ³)
Archer Daniels Midland Co. Dry Mill	300
Archer Daniels Midland Co. Wet Mill	240
Total	540

^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.⁴⁴

^b Data from Liu.³⁴

from 1980 to 2023 is shown in Figure A4. The 10-month average price of DDGS from September 2021 to June 2022 is \$242.31 per ton, up from \$229.24 per ton last marketing year. For the week ending July 28, 2023, DDGS prices averaged \$194.72 per ton in Iowa and \$233.75 per ton in Kansas.

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 has demonstrated high yields of xylose and arabinose carbohydrates produced from DDG using dilute acid hydrolysis, producing upwards of 300 g of sugars per kilogram of dry DDG. They further demonstrated isolation and recovery of xylose in high quantities from the hydrolysate.^{45,46} Cedar Rapids currently produces 300 million gallons of ethanol per year from the dry-grind process, which means approximately a million tons of DDGS is also produced. If 30% of DDGS can be converted to xylose and arabinose, this suggests 0.31 million tons of xylose and arabinose could be produced in Cedar Rapids annually. At \$2,000 per ton for xylose, according to Biocore, a European research program dedicated to investigating second generation biofuels and biomass derived chemicals,⁴⁷ this represents an annual economic value of \$620 million. The \$2,000 per ton price is likely assuming a high purity. Retail price for food grade xylose used as a sweetener is closer to \$1,000 per 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.

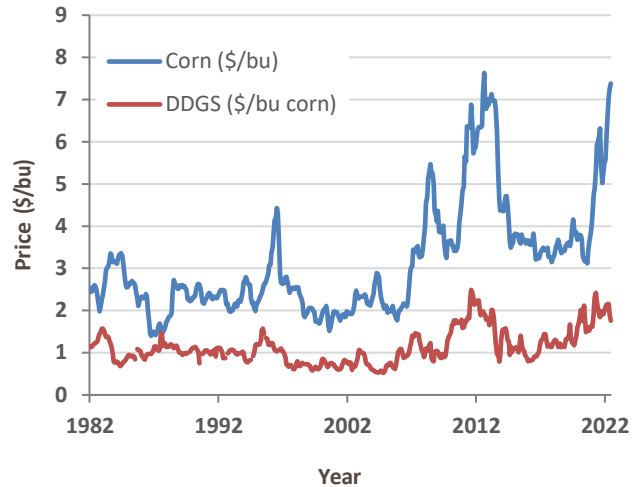


FIGURE 13— Corn and DDGS prices per bushel of corn from 1982 to June 2022.

An example of utilizing the solubles portion of DDGS for higher value applications than recombining with the WDG has been demonstrated by Hu et al. at the University of Minnesota.^{48,49} 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 WDG 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 WDG 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 in 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 per ton to \$10,000 per 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)

WDG are sold in various moisture contents, ranging from 45% to 70%, resulting in a shorter shelf life than DDGS. However, WDG uses less energy consumption from drying, so the production process has lower greenhouse gas emissions and carbon intensity (CI). Switching from producing DDGS to WDG can reduce CI by 8-10 points.⁵⁰ One bushel of corn can produce about 49.5 lb. of WDG. For the week ending July 28, 2023, the prices of WDG (65-70% moisture) ranged from \$62.50 per ton (Iowa) to \$88.25 per ton (Kansas).⁵¹

Figure 14 displays the amounts of various products from the dry mill process in the United States.

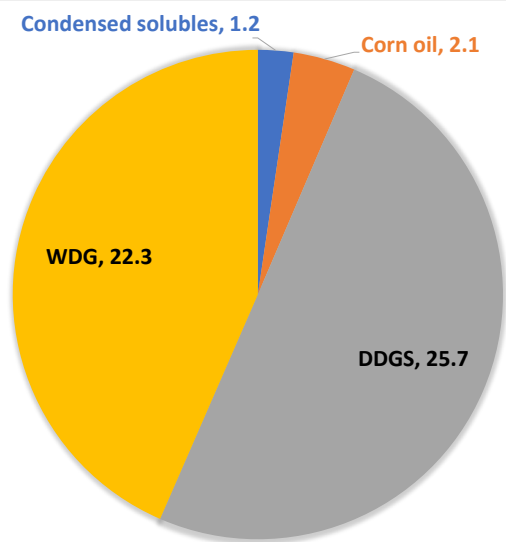


FIGURE 14— Tonnage (million tons) of some U.S. dry mill products for 2022.

Carbon dioxide (CO₂)

Carbon dioxide (CO₂) 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. The carbon capture rate from ethanol production was about 3.7 lb. per gallon of ethanol in 2019.⁵² By weight, approximately one-third of the corn kernel is released as CO₂ during fermentation (6.64 lb. CO₂ per gallon of ethanol, given one bushel of corn can produce 2.86 gallons of ethanol). Nonetheless, the CI of ethanol production is decreasing over time primarily due to increasing corn yield, stable fertilizer application rate, rising ethanol yield, and reduced energy consumption.⁵²

CO₂ captured from ethanol production can be utilized in other production processes, including enhanced oil recovery (EOR), urea synthesis, food processing, and carbonated beverages. Some examples of CO₂ used in food processing are drying fruit and vegetables to extend their shelf life, producing dry ice, and stunning animals before slaughter. The price of merchant CO₂ was typically \$200 per metric ton.⁵³

In addition, CO₂ can be sequestered underground in permitted deep saline aquifers. A reduction in greenhouse gas emissions from ethanol plants is eligible for 45Q and 45Z tax credits. 45Q provides qualifying facilities up to \$85 per metric ton of CO₂ permanently sequestered (equivalent to 4.85 cents per gallon of ethanol) and up to \$60 per metric ton of CO₂ used for EOR (equivalent to 3.42 cents per gallon of ethanol).⁵⁴ 45Z will replace the 40B tax credit after the end of 2024. 45Z offers a tax credit for the domestic production of clean transportation fuels at a rate of up to \$1.75 per gallon for sustainable aviation fuel and up to \$1 per gallon for other transportation fuels. To be eligible for this tax credit, the CI score for ethanol production must be less than 50 kg CO_{2e} per MMBtu. The tax credit rate per gallon of ethanol would be 4 cents per one point of CI score reduction if the facilities meet wage and apprenticeship requirements. Otherwise, they will receive only 0.4 cents per point of CI score reduction per gallon of

ethanol. Studies found that CI for corn ethanol from dry-milling averaged 54.2 kg CO₂e per MMBtu, ranging between 39.7-68.7 kg CO₂e per MMBtu.⁵⁵

Further reduction in corn ethanol CI can be achieved in multiple ways, such as using low-carbon corn (produced by sustainable farming practices), fuel switching, carbon capture and utilization (CCU), and carbon capture and sequestration (CCS) technologies. For example, adding CCU or CCS to a typical dry mill ethanol plant may reduce corn ethanol CI by 32.9-33.8 kg CO₂e per MMBtu.⁵⁶ Replacing half of natural gas use by syngas from biomass gasification or renewable natural gas from animal waste can reduce CI by 11.5-34.9 kg CO₂e per MMBtu.⁵⁶ Moreover, changing from conventional to green ammonia as a source of nitrogen fertilizer can reduce CI score by 6.4 kg CO₂e/MMBtu, while cover cropping is estimated to shrink ethanol CI by 21.5-41.3 kg CO₂e/MMBtu.⁵⁷

A study analyzed life-cycle greenhouse gas emissions of using CO₂ from biorefineries to produce additional ethanol by gas fermentation plus electrochemical reduction processes. The results show that the CO₂-to-ethanol process can possibly reduce greenhouse gas emissions only if renewable electricity is used in the production process.⁵⁸

If capturing, bottling, and shipping is not economically feasible for the CO₂ generated at a facility, a potential more valuable use is as a supercritical solvent for potential on-site applications. Supercritical CO₂ can be used as an effective solvent, catalyst, and extraction phase for xylose conversion to furfural, with xylose being derived from DDGS.⁵⁹ Although high purity CO₂ (99.997%) is required for use in supercritical fluid extraction, so appropriate purification technology would be needed on-site to utilize

the captured CO₂ as a supercritical fluid. Additional discussion of uses for CO₂ are provided in section 4.9.1 of this report.

4.3.3 Water, Waste, and Energy

Water

Water use in the dry-grind ethanol production process is currently estimated at 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 2005.⁶⁰ Further improvements in water usage continued after 2005. Argonne National Laboratory reported that by 2017, on average, 2.65 gallons of water were consumed per gallon of ethanol produced.⁶¹ **Figure 15** gives the average water used in a typical dry-grind ethanol plant in gallons of water per gallon of ethanol produced.^{34,61} There is an overall decrease in the average amount of water used since 1998. If one uses a conservative estimate of 3 gallons of water used per gallon of ethanol (to account for the higher water usage at wet mill facilities, this would equate to roughly 1.6 billion gallons of water used annually in Cedar Rapids for ethanol production.

Energy

Figure 16 gives the total energy use in ethanol plants presented in Lee, Kwon, Wu, and Wang.⁵² Liu et al. showed 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 gallons per bushel over the same time period.³⁴ Energy efficiency and production gains have slowed since then, but the ethanol industry continues to improve metrics. Based on the ethanol capacity of facilities in Cedar Rapids of 540 million gallons and the data in **Figure 16**, the total energy used annually to produce ethanol in Cedar Rapids is 13.5

trillion BTU. Electricity use for ethanol production has been relatively stable over the past decade. For the 2018 report, the authors reported an estimate of 380 gigawatt-hours annually for ethanol production in Cedar Rapids. Given the stability of industry-wide electricity use, that estimate is still appropriate.

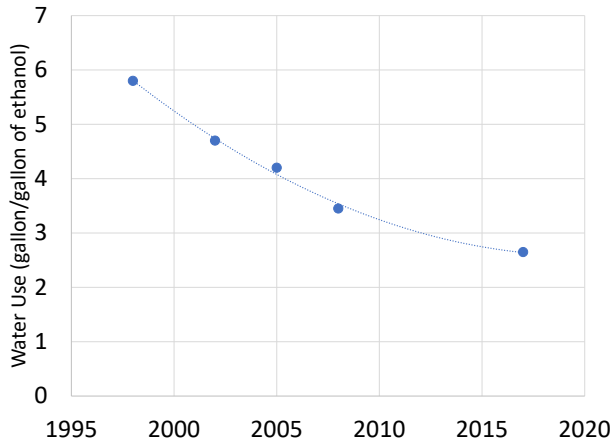


FIGURE 15 – Average water use in dry-grind ethanol plants given in units of gallons of water per gallon of ethanol produced. ^{60, 61}

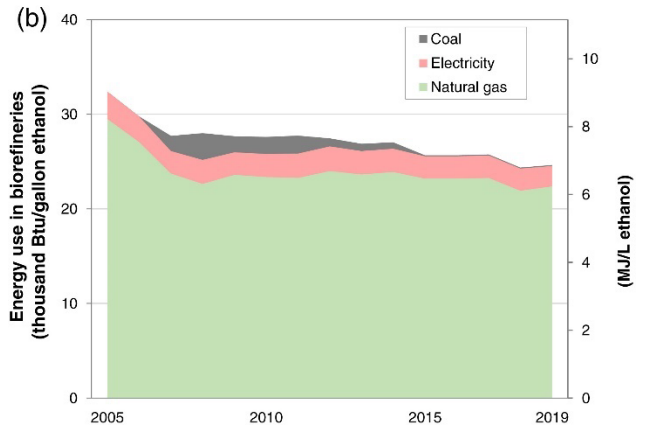


FIGURE 16 – Energy use in ethanol production. This figure originally was published as Figure 3(b) of Lee, Kwon, Wu, and Wang.⁵²

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.²⁶ The major and intermediate steps of the corn wet milling process are outlined in Figure 17. The numbers in Figure 17

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.⁶² By 2022, wet-mill corn processing had retreated back to 888 million bushels.³⁰ Wet milling in Cedar Rapids represents nearly 10% of total wet milling in the United States.

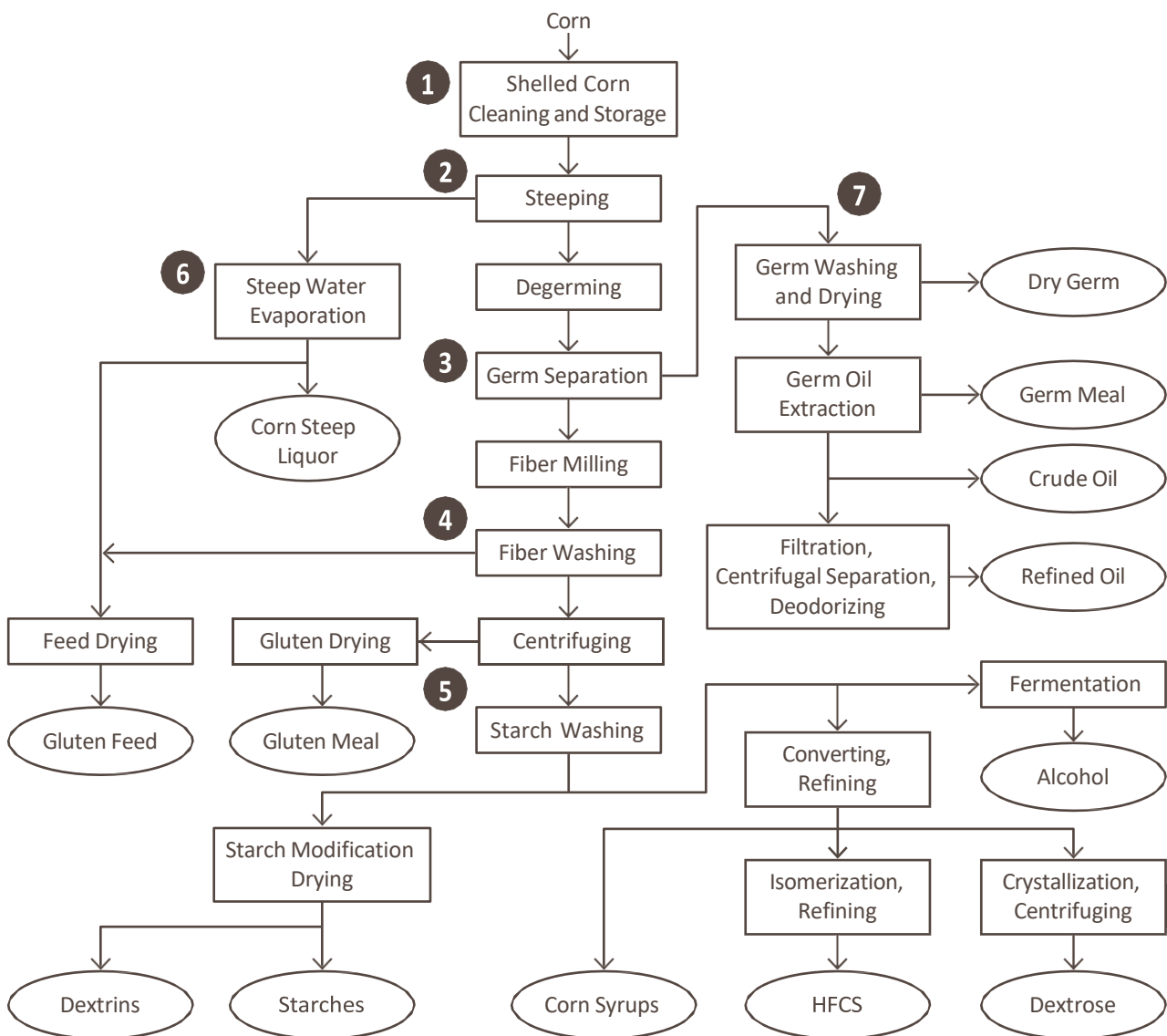


FIGURE 17 – Corn wet milling process (adapted from *Technology of Corn Wet Milling and Associated Processes*).²⁷ Process steps are outlined in boxes and products are outlined in ellipses.

(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 (SO₂) concentration, and recirculation conditions. Cleaned corn enters steeping with a moisture content of 16 wt% and steeping increases the moisture to approximately 45 wt%.⁶³ Low concentration SO₂ (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.⁶⁴ 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 the 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 SO₂ to the desired concentration. This method of operation allows for the newest corn to encounter the lowest SO₂ concentration where the *Lactobacillus* bacteria will be least inhibited. Overall, the amount of water used in steeping is approximately 0.9-1.2 m³ per ton of corn (6-9 gallons per 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.^{63,65} 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.^{65,66} 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.⁶⁷

(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.⁶⁸ Normally 80-85% of the measured total oil in the corn is recovered in the germ-separation process.⁶³

(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.⁶³ 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.⁶⁹ 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.⁷⁰

(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.^{63,68,71}

(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. Corn gluten feed 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.⁶³ 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.⁶³

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).²⁷

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

Starches

Starches are the major output of corn wet milling by weight (generally 31-32 lb. per bushel of corn). In the food industry, starch can be used as food additives for thickening, preservation, adhesion in baked foods, and a quality enhancer in confectioneries, pasta, mayonnaises, salad dressings, etc. Starches are used in many industries for non-food applications, including ethanol, paper, textile, mining, building materials, adhesives or glues, and oil exploration.

Starch from common corn contains 27% amylose and 73% amylopectin.²⁷ Amylose is an unbranched polysaccharide composed of anhydroglucose units. Amylopectin is a polymer chain of anhydroglucose 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 hydroxypropyl groups. Non-

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

Product	Yield ^a	
	(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.⁷²

^b 1 bushel = 25.4 kg (56 lb).

^c Ethanol and sweeteners are produced from the final starch product.

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 2000.⁶³ **Figure A5** shows the price of unrefined corn starch sold in the Midwest from 2002 to 2023. The Midwest price of corn starch was \$389 per ton in June 2023, according to the USDA’s feed grains database. The 10-month average price from September 2022 to June 2023 is relatively stable at \$391.52 per ton, compared to \$389.48 per ton a year earlier.³² 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 (HFCS) is produced by converting some of the glucose into fructose by enzymatic isomerization and mixing glucose and fructose. HFCS has some advantages over sugar, such as a lower freezing point that allows foods to be frozen at a lower temperature without crystallization, and a longer shelf life. Nowadays, HFCS is used in most processed foods, including yogurt, ice creams, ketchup, salad dressings, soups, canned vegetables, and bread. Three major types of HFCS are sold in the markets: HFCS-42 (42% fructose), HFCS-55 (55% fructose), and HFCS-90 (90% fructose). HFCS-90 is used to be blended with glucose to produce HFCS-42 and 55. HFCS-42 is mainly used in processed foods, cereals, baked goods, and some beverages, while HFCS-55 is primarily used in soft drinks. HFCS is well-known to be cheaper than sugar (sucrose), which also contains glucose and fructose. **Figure A6** gives the monthly wholesale prices of HFCS-42 and HFCS-55 from 1994 to 2023 according to the USDA Economic Research Service. In June 2023, the wholesale spot prices of HFCS-42 and 55 were \$845.07 and \$987.01 per ton, respectively. Meanwhile, the wholesale price of refined beet sugar in the Midwest was \$1,240 per ton.⁷³

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).⁷ DE is a measure of the amount of reducing sugars determined by heating the syrup in a reducing solution of copper sulfate. 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 2023. Corn syrup price in the Midwest was \$990 per

ton in June 2023, according to the USDA’s feed grains database.⁴

Dextrose

Dextrose (glucose) is the fully hydrolyzed or depolymerized form of starch often used in baking products, confectionery, low-calorie beers, and dairy products to sweeten foods, extend shelf life, improve fermentation, and improve quality and texture. In addition, dextrose is used medically to treat low blood sugar, especially in people with diabetes mellitus. Dextrose is also used to provide carbohydrate calories to a person who cannot eat and sometimes to treat people who are sick from drinking too much alcohol. Dextrose 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 from 1975 to 2023 according to USDA ERS.⁷³ The wholesale list Dextrose price in the Midwest was \$1,380 per ton in June 2023.

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. They are more water-soluble than starch. Dextrins are mostly used as adhesives for paper products, while only white dextrins are used in the food industry to replace fats in low-calorie foods, add soluble corn fiber, and thicken processed foods like cereals, baked goods, dairy products, protein bars, and salad dressings. The retail price of white dextrin powder is about \$97-\$119 per 500 g, while yellow dextrin powder costs \$935 per 25 kg. Maltodextrin prices are \$600-\$650 per metric ton FOB China in 2022 Q1.

Ethanol

Ethanol is a product of corn wet milling. The ethanol yield from a wet-mill process is generally lower than that of a dry-grind process because wet milling produces more co-products. A 2006 report found roughly a 0.1 gallon reduction in the ethanol yield per

bushel for a wet mill plant versus a dry-grind process. Only five plants in Iowa wet mill, with a total ethanol production capacity of 760.5 million gallons per year (15.7% of the total production capacity in the state). 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. Corn steep liquor contains several vitamins, minerals, lactic acid, and organic nitrogen, which is suitable for fermentation. Additionally, corn steep liquor can be combined with corn gluten feed to feed animals such as cattle, swine, and poultry. 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.²⁷ 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. **Figure 18** displays the raw tonnage of gluten feed and meal produced by U.S. wet mills. Gluten feed contains the fiber (bran) of the corn and is often blended with steep water solids and germ meal.

Gluten feed 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.²⁷ Corn gluten feed is often used in ruminant, poultry, and swine feeds. Corn gluten feeds are sold as wet gluten feed, which contains about 50-60% moisture, and dry corn gluten feed. While wet corn gluten feed has some nutritional advantages over dry gluten feed, wet gluten feed has a very short shelf life (a few days in summer and 1-2 weeks in winter). The Midwest price of dry corn gluten feed (21% protein) was approximately \$161.98 per ton in June 2023. The price for the week ending August 4, 2023, ranged between \$144-\$180 per ton in the central United States, and wet corn gluten feed sold at the prices of \$40-\$75 per ton. **Figure A9** gives the price of corn gluten feed in the Midwest from 1981 to 2023. 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. It is primarily used as a supplement in feeds for livestock, poultry, fish, and pets. In addition, corn gluten meal is known to be able to prevent some kinds of weed seeds from germinating, such as crabgrass, foxtails, dandelion, and pigweed. The centrifugal separation of gluten and starch described in step 5 in the process section can achieve protein levels over 70%; thus, low grade starch is often mixed with the gluten meal to obtain the final specifications.²⁷ The U.S. Midwest price of corn gluten meal was \$508.93 per ton in June 2023, the lowest since October 2021. **Figure A10** gives the price of corn gluten meal in the Midwest from 1981 to 2023. For the week ending August 4, 2023, corn gluten meal prices ranged between \$500-\$560 per ton in the central United States. 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.

Corn 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, phospholipids, color bodies, odors, flavors, pesticides, aflatoxin, metals, oxidative byproducts, and milling residues.⁶³ 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.

Corn oil has a high nutritional value from high vitamin E, polyunsaturated fatty acids (PUFAs), and omega-6 acids. It has a high smoke point, making refined corn oil a good frying oil. Other food products containing corn oil include salad dressings, chips, sauces, bread, cookies, cereals, and margarine. In addition, corn oil is a feedstock for biodiesel and renewable diesel. Corn oil is also used in other industrial products, such as soap, paint, inks, textiles, and insecticides. The crude corn oil (edible) price in Chicago, IL, at the end of 2022 was \$1,200 per ton. **Figure A11** provides historical prices of crude corn oil and distillers corn oil from 2014 to 2022. Corn oil amounts to 1-2 lb. 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.²⁷ 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.

Zein protein

Zein is the major storage protein of corn, accounting for 35-65% of the protein in corn. Despite its high protein content, zein has low nutritional value due to the lack of two essential amino acids (tryptophan and lysine). In addition, negative nitrogen balance and poor water solubility make it less suitable for a direct human food ingredient. Originally, zein protein was mainly incorporated into animal feed. Commercial zein production started in 1939 as zein protein has potential uses in various industries. The water insolubility, resistance to grease, and glossy appearance of zein makes it a promising material for many industrial applications, including fiber, textile, adhesive, biodegradable plastic, films and coatings, pharmaceuticals, and cosmetics. Zein can be used to substitute petroleum-based and synthetic materials in those industries as a more environmentally sustainable material.

Zein is usually extracted from corn gluten meal (CGM) during the corn wet-milling process, DDGS, and dry milled corn (DMC) during the dry-grind process. However, CGM is the most common source due to higher protein content than other co-products (CGM: 50-74% protein, DDGS: 28-30% protein, and DMC: 6.8-8.0% protein).⁷⁴ The zein extraction process typically uses aqueous alcohol as a solvent. Purification, such as removing yellow pigments and odor, can be conducted to obtain a higher quality of zein. Nevertheless, the application of zein requires the development of low-cost manufacturing methods. The cost of purified zein ranges between \$20-\$70 per kilogram, depending on the grade and purity, whereas other alternatives are usually cheaper. For example, the global price of high-density polyethylene (HDPE) was only \$1.11 per kilogram in 2022,⁷⁵ while U.S. HDPE price (below molding grade) FOB Texas was 1.41 per kilogram in December 2022.⁷⁶ To increase the competitiveness of

zein, further research on extraction methods to reduce the production cost is needed, combined with an increase in demand for biodegradable plastics and films.

Zein fibers were commercially sold as Vicara from 1948 to 1957; however, the market was then dominated by synthetic fibers, and zein-based fibers eventually disappeared. One of the promising applications of zein protein is coatings. Edible films made from zein can be used in food products to increase shelf life and prevent loss of moisture, rancidity, and mold growth. Zein has been approved by the U.S. Food and Drug Administration (FDA) as a generally recognized as safe (GRAS) food substance. The commercial use of zein as an alternative coating material began when a shortage of shellac (a coating material produced by an insect) was experienced during World War II. Zein can be used for coating candies, nuts, fruits, and pharmaceutical tablets. However, shellac or vegetable wax is more common in fruits, nuts, and candies. Currently, zein price is generally higher than shellac, but both costs are competitive because less zein is required in solution.

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 counter-current 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 m³ per metric ton of corn.⁷⁷ This amount of water seems to be a reasonable estimate considering the steeping described above in the process steps uses 0.9-1.2 m³ 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 m³ per metric ton of corn is equivalent to 10 gallons per bushel of corn. With corn wet-

milling capacity in Cedar Rapids currently listed at 240 million bushels per year, this calculates to roughly 2.4 billion gallons of water potentially 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 19**.⁷² The estimated energy consumption for the major operations in a wet milling plant are given in **Table 14**.⁷² These numbers are based on a 100,000 bushel per 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 per bushel, whereas in 2007 the energy use ranged from 114,000 to 143,000 BTU per bushel.⁴³ This nearly 50% reduction in energy use is attributed to modern energy-saving technology and process optimization.

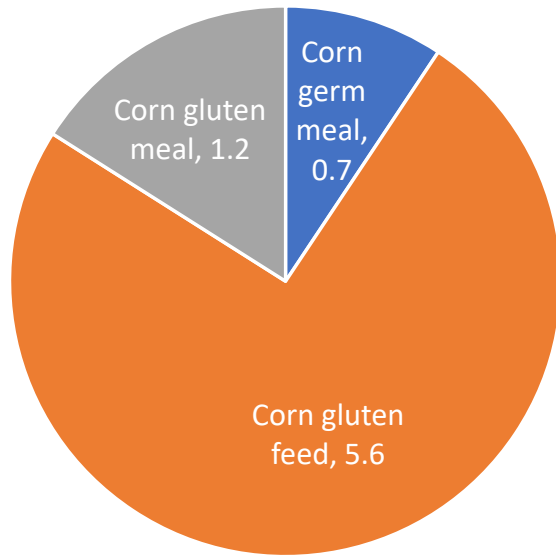


FIGURE 18 – Tonnage (million tons) of some U.S. wet mill products for 2022.

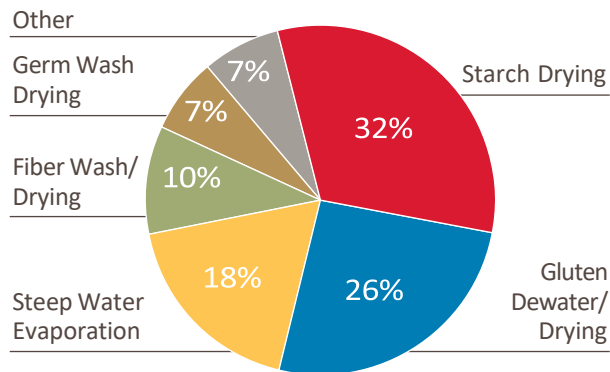


FIGURE 19 – Proportional energy use for major steps in wet milling process.

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

Operation	Energy consumption	
	kJ/bu ^b	BTU/bu ^b
Corn receiving	1,370	1,300
Steeping	4,010	3,800
Steep water evaporation	22,300	21,100
Germ recovery (1st grind)	2,220	2,100
Germ recovery (2nd grind)	1,160	1,100
Germ recovery (washing)	106	100
Germ dewatering and drying	8,550	8,100
Fiber recovery	6,960	6,600
Fiber dewatering	1,270	1,200
Protein (gluten) recovery	3,300	3,100
Gluten thickening and drying	5,380	5,100
Starch washing	1,580	1,500
Starch dewatering and drying	37,100	35,200
Gluten feed dryer	26,800	25,400
Total	122,400	116,000

^a Data from Galitsky.⁷²
^b 1 bushel = 25.4 kg (56 lb.).

4.5 OATS

Oat production and price per bushel from 1975 to the present are given in **Figure 20**. A bushel of oats weighs 32 lb. 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.⁷⁸ 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.^{79,80} The total oats produced and net imported to the United States was 3.1 million tons (193 million bushels) in 2007.⁴ Thus, in that year, Quaker Oats in Cedar Rapids processed 4% of the total available oats in the United States. In 2023, Quaker Oats noted that the Cedar Rapids plant processes over 2 million pounds of oats per day. That translates to over 22.8 million bushels of oats per year. Treehouse Foods owns the former National Oats plant and processes a significant quantity of oats in Cedar Rapids. The United States produced approximately 57.65 million bushels of oats and imported 84.06 million bushels of oats in 2022, with over 90% of the imported oats coming from Canada. Based on USDA oat usage data, oat processing in Cedar Rapids accounted for over 16.5% of total oats processed in the United States in 2022.⁴ As shown in **Figure 20**, oat production in the United States has slowly declined over the past couple of decades. Meanwhile, oat imports have been relatively constant between 80-100 million bushels per year over the same time period.

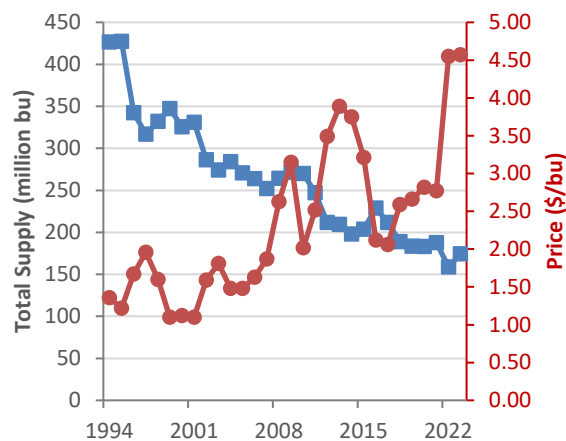


FIGURE 20—U.S. oats production and average annual price (June–May).

4.5.1 Process

The flow diagram for oats processing is shown in **Figure 21**.¹⁴ Oats can be stored up to a year under proper storage conditions: 20°C, 12-14% moisture, and with 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.¹⁴

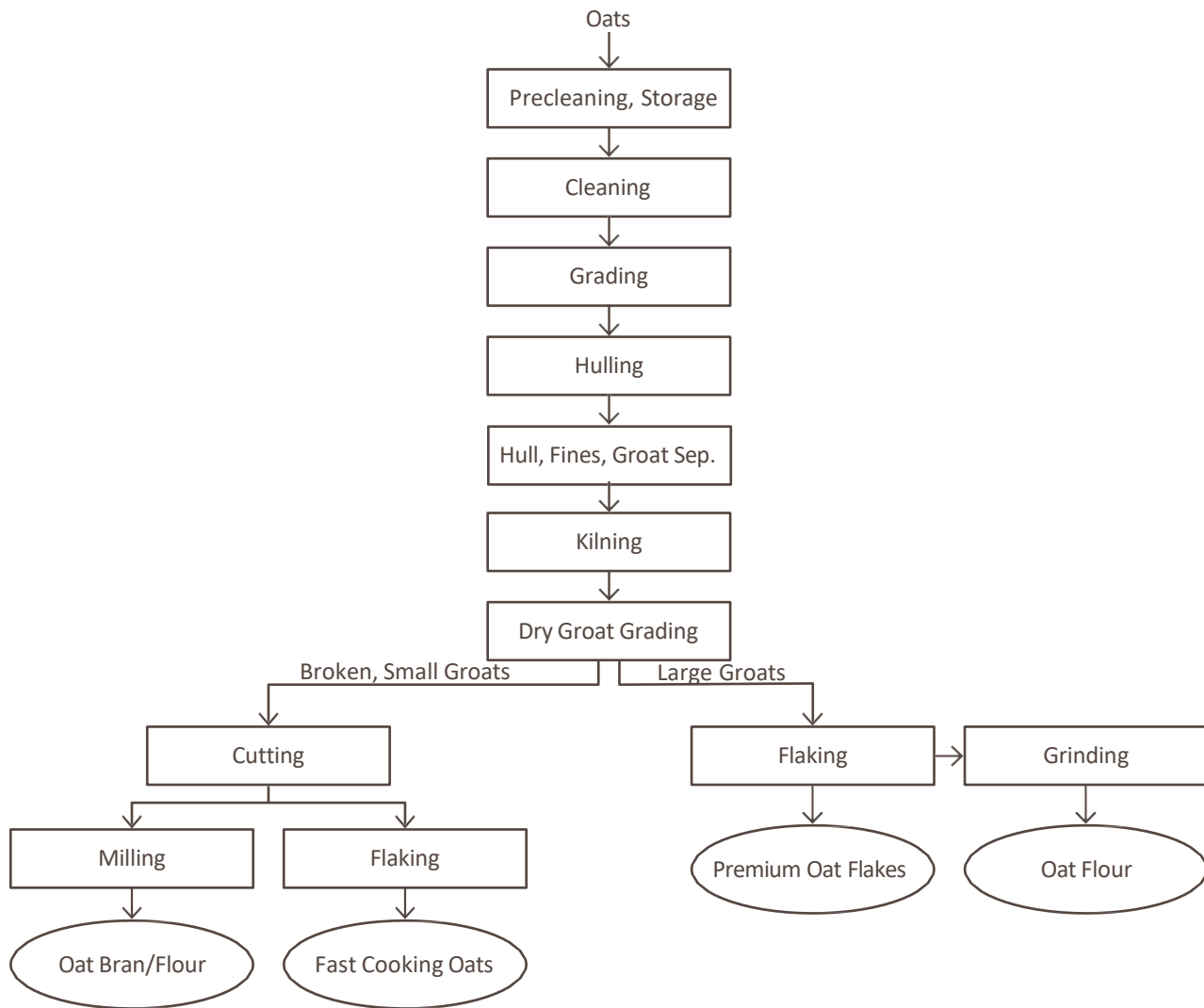


FIGURE 21 – Oat processing flow diagram. Recreated from *Cereal Grains for the Food and Beverage Industry*.

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 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.¹⁴ 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 groats

The oat groat is the whole oat grain with the hull removed, containing bran, endosperm, and germ. Oat groats account for approximately 27% of total oats processing. Whole oat groats retail for approximately \$1.00-\$1.20 per pound.

Oat bran

Oat bran is the outer layer of the oat groat and has a high fiber content. It is used to produce hot and ready-to-eat cereals, porridges, and baked goods. 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 \$1.50 per pound.

Oat flour

Oat flour is finely-ground rolled oats. 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.¹⁴ Oat flour accounts for approximately 14% of total oats processing. As of August 10, 2023, the bulk oat flour FOB price in St. Ansgar, Iowa was \$520 per ton. Meanwhile, the price of organic oat flour was at \$925 per ton at the same location.⁸¹

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.¹⁴ Fast cooking oats account for approximately 7% of total oats processing. Fast cooking, a.k.a. instant oats, retail for approximately \$2.50 per pound, or \$5,000 per 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.⁸² 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.⁸² The Quaker Oats plant in Cedar Rapids, Iowa, produced approximately 40,000 tons of oat hulls per year in 2009.⁷⁸ 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.⁸³ Total oat hull production at the Fridley plant is quoted as 2,000 tons per year.⁸⁴ However, the major usage for oat hulls is in livestock feed. Oat hulls account for roughly 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 FOB in St. Ansgar, Iowa was \$560 per ton on August 10, 2023.⁸¹

Oat feed

Oat feed is a pelleted byproduct of oat milling and contains oat's outer hairs, husks, and sometimes oat bran. It has highly digestible fiber and beta-glucan, which is soluble fiber and is often used as a part of horse feed. On August 10, 2023, the pelleted oat feed price FOB St. Ansgar, IA, was \$195 per ton.⁸¹

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 2022 is shown in **Figure 22**. 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 587 million bushels in 2022, which is 13.7% of total U.S. production.¹² The amount produced in Linn County was 6.835 million bushels harvested from 105,800 acres, which is 1.16% of total Iowa production and 0.16% of total U.S. production in 2022.¹² At an average price of \$14.20 per bushel in 2022, Linn County soybean crop production generated \$97 million in gross value. The average soybean yield in Linn County was 64.6 bushels per acre, which is approximately 6 bushels per acre higher than the state average yield.⁸⁵

In 2017, there were two soybean processing facilities located in Cedar Rapids, and according to industry experts, these facilities processed approximately 100,000 bushels per day in total, or 36.5 million bushels per year, which represents approximately 6.4% of the total soybeans harvested annually in Iowa. Based on 2022 crop data, Cedar Rapids' soybean processing consumes roughly 70% of the soybeans grown in the eight-county region surrounding Cedar Rapids. Given Iowa's average soybean yield of 58.5 bushels per acre in 2022, it takes 623,932 acres of Iowa farmland to fulfill Cedar Rapids' soybean processing needs.

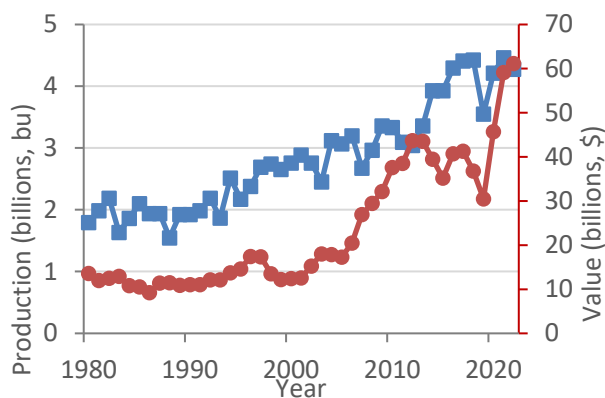


FIGURE 22— U.S. soybean production and gross value.

4.6.1 Process

The typical soybean process is outlined in **Figure 23** 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 specification.²⁴ 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.⁸⁶

(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 is due to combining drying into the dehulling operation.⁸⁷

(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.⁸⁷

(4) Extraction is the next major processing step where the soybean flakes are flowed counter-currently with hexane, an extraction solvent. 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, or 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.^{88,89}

(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 21. 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.⁸⁷

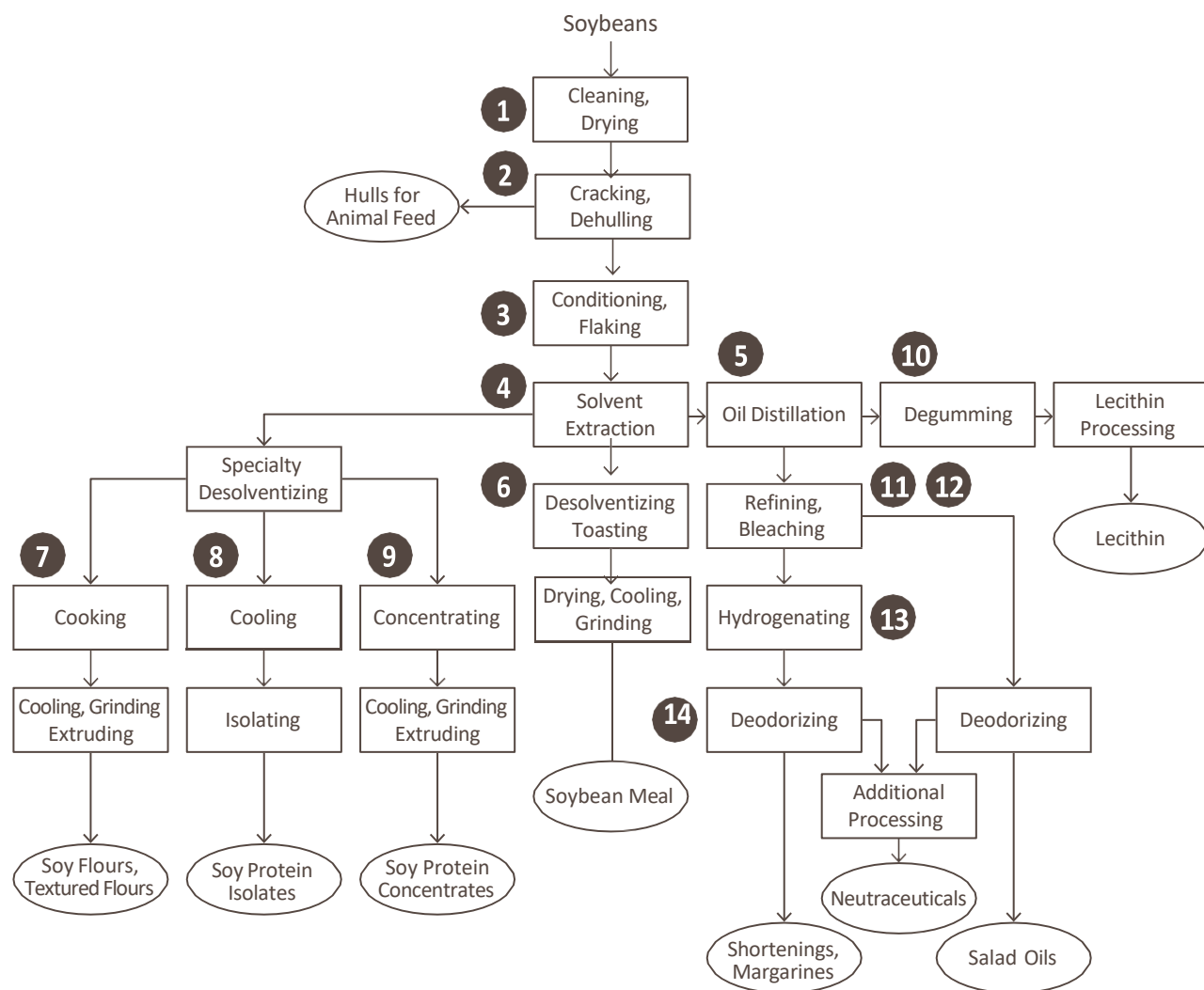


FIGURE 23 – Soybean processing flowchart. The numbers listed in the flowchart correspond to the numbered paragraphs in this section. The steps are not necessarily performed sequentially as numbered. Recreated from National Oilseed Processors Association.⁹⁰

(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 flows 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.⁹¹

(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. 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.⁹²

(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.⁹²

(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. 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.⁹³ Uses of soy protein concentrates include applications requiring a low-flavor profile, water- and fat-absorption, emulsification, and other nutritional uses.⁹²

(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 (three 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 of <1% and cooled to 20-30°C where it can be stored for over a year without changes in quality or properties.⁹⁴

(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 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 free fatty acids in the oil plus a slight excess.⁹⁵

(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.⁹⁶

(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 occur, thus creating 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.⁹⁷ Although oil hydrogenation has been performed for over a century, it is still an active area of research.⁹⁸ 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.^{99,100,101} 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.¹⁰²

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

Soybean oil is one of the major products of soy processing. According to the USDA, the soybean oil extraction rate for the 2021/22 year was 11.75 pounds per bushel (20% of soy weight).¹⁰³ For food applications, soybean oil is widely used as a cooking oil due to its high smoke point, polyunsaturated fats (omega-3 and omega-6 fatty acids), and vitamins E and K. Soybean oil is also used in various types of food products, such as baked goods, snacks, salad dressings, and sauces. Industrial applications of soybean oil include massage oils, hair moisturizers, inks, paints, varnishes, and resins used in automotive or aerospace industries. The average crude soybean oil price is estimated at \$1,459.60 per ton for the 2021/2022 year and is forecasted to be at \$1,320 per ton for the 2022/2023 year, according to the USDA oil crop yearbook.¹⁰⁴ For the week ending August 11, 2023, soybean oil prices ranged between \$1,382.60-\$1,422.60 per ton in Iowa.¹⁰⁵ Historical soybean oil prices are given in **Figure A12**.

Soy flours

Soy flour is produced from dehulled soybeans, which can be full-fat, defatted, refatted, and lecithinated flours. Soy flour has higher fiber and protein than all-purpose flour. Soy flour can be substituted for up to 30% of the all-purpose flour in baked goods without making any other adjustments. Since soy flour is gluten-free, it is often included in gluten-free bread mixes. In addition, coarsely grounded soy flour can be used to thicken gravy and sauces. Full-fat soy flours are prepared from dehulled soybeans which have not undergone extraction. 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 re-fatted or re-

lecithinated.⁹² Soy flour is approximately \$500 per ton.

Soy protein isolates

Soy protein isolate (SPI) is produced by separating fiber, carbohydrates, fats, and other nutrients from soy protein. Hence, SPI contains high protein (90%) and phosphorus. SPI can be used in dairy products (such as formula milk powder, liquid milk, and non-dairy beverages), meat products as a functional additive or non-functional filler (adding to sausages), baked goods, and pasta, to improve food quality and nutrition. 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 SPI. SPI retails for approximately \$2,000-4,000 per 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.⁹² Soy protein concentrates can be used to increase water retention, improve texture and emulsification, and maintain nutritional values. Applications of soy concentrates include meat, poultry, fish, meat alternatives, ice cream, dairy replacements, protein beverages and bars, soups and sauces, and pet food. The retail price of soy protein concentrates is \$1,000-\$1,300 per ton.

Soybean meal

Soybean meal is produced from the desolventized-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).⁹¹ One bushel of soybeans generally yields 48 lb. of soybean meal. Soybean meal is primarily used as poultry feed (56%). Swine, beef, and dairy feed account for 25%, 8%, and 7%, respectively, of

its use.¹⁰⁶ Historical soybean meal prices are given in **Figure A13**. The average price of soybean meal is estimated at \$439.81 per short ton in the 2021/22 marketing year, and USDA forecasted the average price to be at \$465 per short ton in the 2022/23 year. Meanwhile, the futures prices of soybean meal on the CBOT expiring in December 2023 averaged \$395.90 per short ton in July 2023.¹⁰⁷

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 per ton.¹⁰⁷ For the week ending August 11, 2023, one ton of soy hulls in Iowa cost about \$200-\$220.¹⁰⁵

Lecithin

Lecithin is separated from soy oil and contains polyunsaturated fatty acids, vitamins K and E, and very low soy protein. 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.¹⁰⁸ Wholesale soy lecithin costs approximately \$2,150 per 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 reviewed article describing the potential of using soybean carbohydrates as fermentation feedstocks for production of biofuels,

enzymes, and specialty chemicals.²⁵

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.¹⁰⁹ National Oilseed Producers Association (NOPA) surveyed 15 soybean processing plants in 2008 and obtained information on water, energy, and waste production.¹¹⁰ 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.¹⁰

^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 2003.¹¹¹ Production has undoubtedly grown since then. Cedar Rapids has been a growing power in yeast production. The Red Star/Lesaffre facility is thought to be the world's largest production facility, producing the yeast for roughly 40% of the bread made in North America.¹¹² While exact production numbers are not available for the yeast industry, IBISWorld estimates that the U.S. yeast sector captured \$913 million in 2022. As Cedar Rapids' production has been expanding, national production has declined slowly over the past five years as yeast imports have increased.¹¹³ *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. cerevisiae*, 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).¹¹⁴

A process flow schematic of the overall yeast production process is shown in Figure 24. 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 are 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, stored, 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. The mineral salts 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.¹¹¹ 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

Liquid yeast is a live culture, so it is typically more expensive and more perishable than dry yeast. The shelf life of liquid yeast shipped by mail order is typically three months. The benefits of liquid yeast are freshness and the range of available strains. Liquid yeast is commonly used for home and commercial breweries.

TABLE 16 – Yeasts for baking applications^a

Application	Genus	Species
Multipurpose	<i>Saccharomyces</i>	<i>cerevisiae</i>
High-sugar doughs	<i>Saccharomyces</i>	<i>rosei</i>
	<i>Saccharomyces</i>	<i>rouxii</i>
Favor enhancement	<i>Saccharomyces</i>	<i>delbrukii lusitaniae</i>
Sourdough starters	<i>Saccharomyces</i>	<i>exiguus holmii milleri</i>

^a Table recreated from Poitrenaud.¹¹¹

Liquid yeast products are more popular in Australia and the United Kingdom than in North America.¹¹⁴ Vegemite is an example of a product made from liquid yeast.

Compressed yeast

Compressed yeast is a fresh cream yeast in the form of small blocks, which limits the exposure to oxygen. It contains approximately 70% moisture and 30% solid. Although compressed yeast has a lower shelf life than dry yeast, it can be frozen and stored for several months.

Crumbled yeast

Crumbled yeast is fresh yeast crumbled into small pieces. It is typically sold in sealed plastic packaging, so it is more sensitive to oxygen exposure because of its large surface area. Similar to other fresh yeast products, crumbled yeast has a shelf life of three weeks and should be stored in refrigerated storage.

Active dry yeast

Active dry yeast is a dehydrated and dormant form of yeast stored in the form of dried granulates. The prominent benefits of active dry yeast are a very long shelf life and the ability to store it at room temperature for several months before it loses potency. It is one of the most common forms of yeast in home baking. Active dry yeast must be rehydrated before use.

Instant dry yeast

While active dry yeast needs to be dissolved in water before use, instant dry yeast can be mixed right into dry ingredients. Instant dry yeast is dry yeast in smaller granules than active dry yeast, absorbs liquid rapidly, and does not need to be rehydrated. Hence, instant yeast is one of the most preferred choices for bread baking.

Free-flowing frozen dry yeast

Free-flowing frozen dry yeast is an instant active dry yeast specially developed for frozen dough. It has lower moisture content and helps improve the stability and storage of frozen dough to meet the

growing demand for frozen products and long-distance shipments.

Dry yeast with reducing power

Dry yeast with reducing power (active form) comes in granulated forms and is mainly used for pizza making due to moderate gas production during fermentation. Deactivated dry yeast has no fermenting power but can be used to improve the workability of the dough and reduce kneading time.

Other product applications

Yeast-based biofertilizer and biopesticide are byproducts of the yeast production process created while separating the yeast from a liquid medium. The fermentation broth recovered can be concentrated, dried, and used as a biofertilizer to supplement or substitute synthetic fertilizer. Yeast has the potential to act as biostimulant, biofertilizer, and biopesticide. Yeast can enhance nutrient efficiency, crop quality, and tolerance to abiotic stress. Research found that adding live or dead yeast can improve plant nutrition, especially nitrogen and phosphorus.¹¹⁵ Furthermore, brewer's yeast extract hydrolysate can prevent bacterial and fungal diseases and enhance the plant's natural defense mechanisms. Despite the potential benefits, the commercialization of yeast-based biofertilizer and biopesticide is currently limited due to challenges on both demand and supply sides, such as difficulty in marketing as the product contains live organisms, a short shelf life, and a lack of awareness and experience of its application.

Yeast can be used as a feed supplement for cattle, poultry, swine, and other animals. *Saccharomyces cerevisiae* is commonly used as bakers' and brewers' yeast as well as animal feed. The use of yeast cultures in animal diets has several potential beneficial effects, such as improved nutrient digestion and reduced rumen acidosis risk in cattle. Yeast cultures are not a nutrient source; however, some types of yeast, such as brewers' yeast, contain biomass as well as valuable minerals and vitamins.¹¹⁶

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.

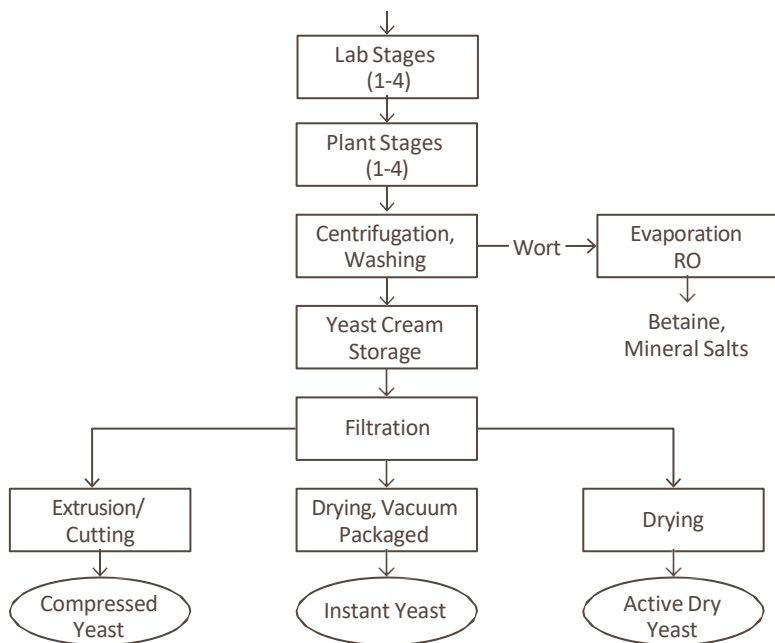


FIGURE 24 – Baker’s yeast manufacturing process flow chart.

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 including size reduction, mixing, separation, irradiation, heat and pressure treatments, blanching, pasteurization, evaporation, sterilization, extrusion, dehydration, smoking, baking, roasting, frying, chilling, freezing, coating, and 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. Interested readers may consult the textbook, *Food Processing Technology*,¹¹⁷ for thorough evaluations of each of the processing operations mentioned above.

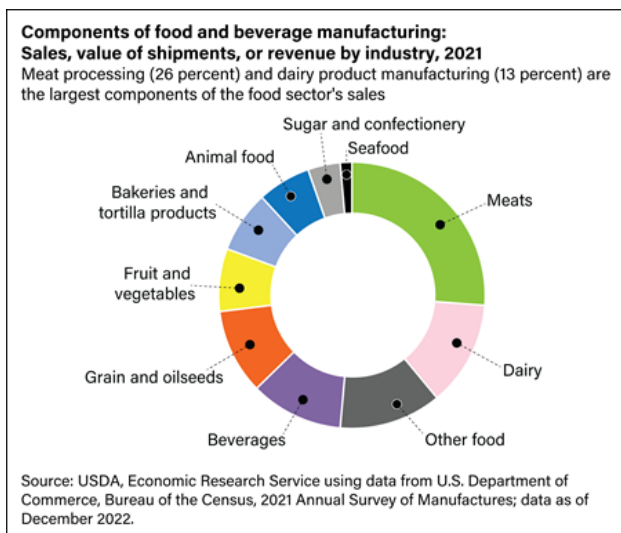


FIGURE 25 – U.S. food and beverage manufacturing value of shipments¹¹⁸

Based on the 2021 Annual Survey of Manufacturing from the U.S. Department of Commerce, the food and beverage manufacturing industry processed and shipped over \$1 trillion of products. USDA compiled the following graphics to show the relative sizes of the various subsections of the industry. **Figure 25** outlines the percentages of the value of shipments for the food and beverage manufacturing industry. **Figure 26** displays the proportions of value added within the industry.

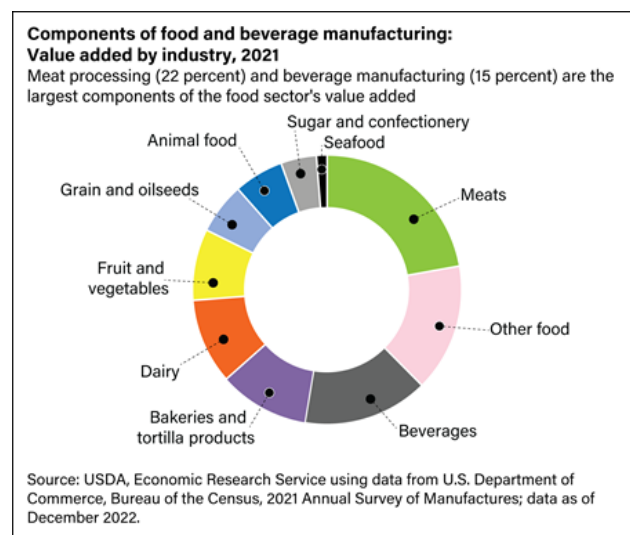


FIGURE 26 – U.S. food and beverage manufacturing value added¹¹⁸

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 needing less cleaning, the ability to handle viscous, oily, or high sugar materials, and easier operation compared to single screw.¹¹⁷

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 is generally lower in costs than other methods and can produce a variety of products and shapes that are not easily produced by other methods. Extrusion itself does not produce any effluents or create any water treatment costs.¹¹⁷ 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 per kilogram for high shearing operation and 0.01-0.04 kWh per kilogram for low shearing operation with kilogram indicating the mass of the processed product. Using extrusion for breakfast cereal manufacturing 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.¹¹⁷

The physical phenomena of baking reduces 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 takes longer than crackers. Crust formation, which is caused by rapid heating that can lead to physical, chemical, or morphological changes at the surface, is an important phenomenon for some foods. 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.¹¹⁷ 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. 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.

4.9 FEEDSTOCKS FOR ADDITIONAL DEVELOPMENT

Within the Cedar Rapids food and bioprocessing sector, there are two co-products being highly sought after for additional development—CO₂ and corn oil.

4.9.1 Potential for new businesses with CO₂ as a feedstock

Two of the largest industrial consumers of carbon dioxide are enhanced oil recovery (EOR) and urea synthesis. Globally, urea production accounted for 57% of the total CO₂ consumption (around 130 million tons), while EOR consumed 34% (70-80 million tons) in 2015.¹¹⁹ The remainder is used in other industrial sectors, including carbonated beverages, food processing, and metal fabrication. In the United States, EOR is the biggest user of the CO₂ market, accounting for 77.3% of total consumption.¹²⁰ The CO₂ for EOR and urea synthesis in the United States are mainly from natural CO₂ wells. Other sources of CO₂ include CO₂ captured from industrial plants, especially ethanol, ammonia, and hydrogen.

In addition, CO₂ is widely used in the food and beverage industry for applications such as removing the caffeine from coffee beans to make decaffeinated coffee, carbonating beer and soft drinks, drying fruits and vegetables to extend shelf life, as dry ice for goods refrigeration in transit, stunning animals before slaughter, etc.

The latest shortage in food-grade CO₂ occurred in August 2022 due to foreseen and unforeseen supply disruptions. Ammonia manufacturing plants regularly shut down for maintenance at the end of summer when demand for fertilizers is low. In the meantime, several ethanol plants closed for unscheduled maintenance. These temporary plant shutdowns decreased total CO₂ supplies by approximately 30-40%. The market tightness was exacerbated when the supply from Jackson Dome, one of the five major natural CO₂ reservoirs in the United States, was contaminated by an extinct volcano. Contaminated CO₂ cannot be used in beverages due to the changes in

tastes and smells. This issue removed 25-30% of the beverage-grade CO₂ supply from the market. These supply disruptions caused a shortage of CO₂ in many industries, such as beer, soda, and meatpacking. Although CO₂ gas contamination is unlikely to happen frequently, the 45Q tax credit may incentivize industrial plants to store their captured CO₂ underground, which is more profitable than selling in the CO₂ merchant market.

Enhanced Oil Recovery (EOR)

As of 2020, there were 142 CO₂-EOR projects in the 48 contiguous states, producing 273 million barrels per day. While EOR is the major consumer of CO₂ in the United States, the supply of industrial CO₂ captured is typically required to be transported via pipeline or other means. One ton of industrial CO₂ can cost up to \$30 delivered, and each ton can yield 2-3 barrels of oil. Less than 20% of CO₂ is supplied by industrial sources. Unfortunately, none of the CO₂-EOR projects are using CO₂ captured from manufacturing facilities in Iowa and Illinois, primarily due to the distance and unavailability of CO₂ pipeline to oilfields with EOR.

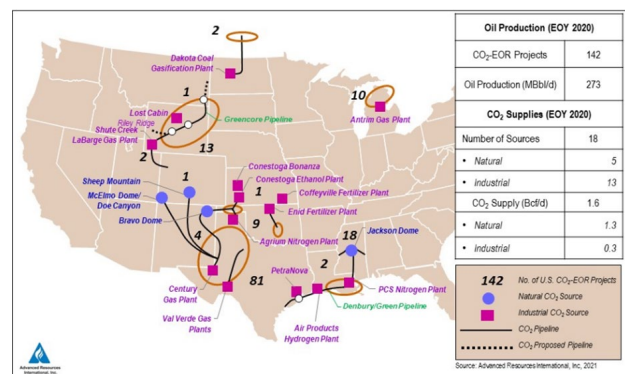


FIGURE 27 – U.S. CO₂-EOR projects and sources of CO₂ in 2020.¹²¹

Urea Synthesis

Urea is the world’s most common and commonly used nitrogen fertilizer and the third-most consumed nitrogen fertilizer in the United States after nitrogen solutions and anhydrous ammonia. The total U.S. urea production capacity was 12.9 million tons per year in

2021.¹²² In the meantime, the U.S. urea consumption was approximately 6.4 million short tons (gross weight). A portion of urea is used as a feedstock for nitrogen solutions; hence, the United States is the third-largest net importer of urea, with net imports of 6.2 million tons in 2021.

Urea is produced from ammonia and CO₂. About 0.73 tons of CO₂ is required to produce one ton of urea.¹²³ Two urea production facilities are located near Cedar Rapids: (i) Iowa Fertilizer Co. in Wever, IA, with a production capacity of 1.12 million tons per year; and, (ii) Coffeyville Resources in East Dubuque, IL, with a production capacity of 0.175 million tons per year. If these facilities fully operate, they require about 946,000 short tons of CO₂ as a raw material. Nonetheless, these facilities also produce ammonia and have CO₂ as a byproduct. If they capture and utilize the CO₂ from the ammonia production process, they will not need additional CO₂.

Another possible way to utilize CO₂ from ethanol plants and other manufacturing facilities in the city is by attracting new urea facilities, which can obtain ammonia from other sources. A 100,000-ton-per-year urea production plant requires approximately 73,000 tons of CO₂ when fully operational. In addition, if a green ammonia plant, which relies on 100% renewable energy and does not emit CO₂, is built along with the urea plant, it can provide ammonia as a feedstock for urea and sell anhydrous ammonia as a final product to local farmers. The cost per unit of green ammonia is higher than conventional ammonia. With technological progress, green ammonia will soon be produced at a competitive cost or even lower cost. For example, if the cost of clean H₂ is \$1.50 per kilogram or less, green ammonia production cost can be less than conventional ammonia cost even

with an electricity price of \$0.08 per kWh.¹²⁴

U.S. urea prices in New Orleans were \$285-\$317 per ton FOB in June 2023, while the retail prices in Iowa ranged between \$580-\$795 per ton, with an average of \$679.17 per ton. Even though urea prices in 2023 are lower than in 2022, they are still 28% higher than the prices in 2021. Likewise, anhydrous ammonia prices in Iowa averaged \$907.50 per ton at the end of June 2023, translating into a 30% increase from 2021.

Carbonated beverages/breweries

Carbonated drinks include soft drinks, sparkling water, soda, beer, and carbonated wine. CO₂ is dissolved in water under high pressure and low temperature. Soft drinks and sparkling waters typically contain 3.5 volumes of CO₂ (equivalent to about 7 grams CO₂ per liter of drink). If a manufacturing plant produces 10,000 L of soft drinks per hour, it will need approximately 146.16 metric tons of CO₂ per year. Traditional champagne has approximately 4.6 volumes of CO₂, while the carbonation levels in beer depend on the style, ranging from 1.5-5 volumes of CO₂.¹²⁵ The carbonation in beer is typically generated by alcoholic fermentation, but CO₂ is sometimes added to the final product to enhance carbonation.

The CO₂ used in the food and beverage industry is usually highly purified, so the cost is generally higher than CO₂ used for EOR. High-purity CO₂ is mainly generated from ammonia, ethanol, and hydrogen production processes. Other sources can include natural CO₂ wells and natural gas processing. The U.S. CO₂ market has experienced a fluctuation in prices due to increased demand and supply shortage during the COVID-19 pandemic. In the last quarter of 2020, U.S. liquid CO₂ prices ranged between \$450-\$480 per metric ton.¹²⁶ The averages of producer price index of CO₂, published by the U.S. Bureau of Labor Statistics, show a 35.4% increase in CO₂ prices from 2017 to 2022.

Dry ice manufacturing

Dry ice is produced by liquefying CO₂ and then freezing and compressing it into solid ice, which can be utilized in many industries, especially the food industry.

Common applications are removing bacteria and mold in a kitchen or restaurant and preserving food freshness in storage or transit. Other industrial and medical uses of dry ice include blast cleaning, pest control, fire suppression, repairing dents in vehicles, and storage and transportation of temperature-sensitive medical devices, samples, and equipment. The retail prices of dry ice range between \$1-\$3 per pound. Commercial shipping containers for dry ice can contain 200-1,500 lb.

4.9.2 Potential for new applications of distiller's corn oil as a feedstock

Distillers corn oil (also called technical or inedible corn oil) is extracted from distillers grains before the drying process in corn ethanol production. On average, 0.75 lb. of distillers corn oil (DCO) is produced per one bushel of corn.¹²⁷ DCO is different from the common corn oil, which is extracted from a corn germ. Some differences between these two oils are that DCO contains a higher free-fatty acid content than refined corn oil and DCO is not made for human consumption. Distillers corn oil is commonly used as a feedstock for biodiesel and renewable diesel and a supplement for poultry and swine diets. Other applications of corn oil include soap, inks, textiles, moisture-resistant coating for paper substrates, anti-corrosion coating material, cosmetics, etc. In 2022, 4.2 billion lb. of distillers corn oil were extracted in a corn dry-milling process.³⁰ DCO (inedible) price FOB in the eastern Corn Belt was at \$1,390.40 per ton at the end of 2022. Edible corn oil prices were generally higher than inedible corn oil. However, DCO prices have overtaken edible corn oil prices since August 2021, corresponding to rising renewable diesel production capacity in the United States.

Biodiesel and renewable diesel

Seventy-one percent of DCO produced in the United States was used to produce biofuels

(mainly biodiesel and renewable diesel) in 2022. Biodiesel and renewable diesel are biomass-based diesel that can be used to comply with the U.S. Renewable Fuel Standard (RFS). Both are mainly produced from vegetable oils and animal fats, such as soybean oil, corn oil, used cooking oil, tallow, canola oil, and sunflower oil. As large crops in the United States, soybean and corn oil are the top two raw materials for biodiesel and renewable diesel. In 2022, 3 billion pounds of corn oil and 10.5 billion pounds of soybean oil were used to produce biodiesel and renewable diesel.

The main differences between biodiesel and renewable diesel are the chemical composition and production process. The latter is a hydrocarbon fuel, chemically equivalent to petroleum diesel, and typically used in pure form. On the other hand, the former is a Fatty Acid Methyl Ester (FAME), which is not a hydrocarbon fuel. Unlike petroleum and renewable diesel, biodiesel contains oxygen, so it is typically blended with petroleum diesel in various concentrations. The most common biodiesel blend is B20 (6-20% biodiesel) and B5 (5% biodiesel). B20 is compatible with many conventional engines and has good performance in cold weather, while B5 is widely used in fleet vehicles. Compared to renewable diesel, biodiesel is a lower-quality fuel that may damage vehicles' engines and provide less power and efficiency. Additionally, renewable diesel has advantages in terms of greenhouse gas emission reduction over biodiesel. While both biodiesel and renewable diesel can be produced from the same feedstock, their production processes are dissimilar. Biodiesel is produced by converting vegetable oils or animal fats into fatty acid alkyl esters using alcohols and catalysts. This process is called transesterification. About 7.5 lb. of vegetable oils or animal fats are used to generate one gallon of biodiesel and 0.9 lb. of glycerin as a co-product. As renewable diesel has potential environmental and private benefits more than biodiesel, the capital costs for renewable diesel production are considerably

higher than biodiesel production. Renewable diesel is produced from hydrotreatment, thermal conversion, or biomass-to-liquid production processes. Before processing, impurities in oils and fats such as metal, phosphorus, chlorides, nitrogen, and sulfur need to be removed. In the biodiesel production process, on the other hand, these contaminants can be left in the feedstock and removed later through distillation of the final product. Thus, oils and fats that contain fewer impurities, for instance, used cooking oils, canola oil, sunflower oil, and animal fats, are preferred as a feedstock for renewable diesel. However, these raw materials typically cost more than distillers corn oil. In general, 8 lb. of feedstock are required to produce one gallon of renewable diesel.

The production capacity of biodiesel dominated renewable diesel in the United States until June 2022. Renewable diesel production plants have been growing rapidly in recent years. As of January 1, 2023, U.S. biodiesel production capacity is 2.09 billion gallons per year, down from 2.26 billion gallons per year in the previous year.¹²⁸ In the meantime, U.S. renewable diesel and other biofuels production capacity is 3 billion gallons per year as of January 1, 2023, up from 1.75 billion gallons per year last year.¹²⁹ Although the production of renewable diesel has increased over the past years, none of the renewable diesel plants are located in Iowa and Illinois.

Meanwhile, 483 million gallons of biodiesel production capacity is spread across 11 different cities in Iowa. In April 2023, the national average retail biodiesel (B99/B100) price was \$4.95 per gallon, and the average renewable diesel price in California was \$5.24 per gallon.¹³⁰

Biodiesel would still be a good application of DCO, given the size and locations of demand. For renewable diesel, DCO at least needs to be transported to the production plants, which are

out of state. The closest renewable diesel production facilities are in Hugoton, KS, and Dickinson, ND. Additionally, refining DCO may increase the value and demand for the product if the cost of refined corn oil is competitive with other feedstock.

Animal feed

The remaining DCO is mostly used as a supplement for poultry and swine diets. Compared to refined corn oil, DCO has higher free fatty acid content, which is a valuable source of metabolizable energy. A study shows that corn germ oil contains, on average, 5.4% free fatty acids, while corn oil extracted from DDGS has 10.5% free fatty acids.¹³¹ In addition, it is rich in lutein, zeaxanthin, and linoleic acid, which are essential for poultry and swine. The low prices of DCO relative to other types of vegetable oils and its abundance partly contribute to the use for animal feed. Another benefit of extracting corn oil from distillers grain is that DDGS extracted oil is more suitable for dairy and beef cattle feeds because it contains a lower fat content.

Other potential applications of corn oil

Corn oil is one of the raw materials for oleochemicals, which have a wide range of applications, including soap, paint, inks, textiles, cosmetics, and personal care products. Corn oil can also be used as a moisture-resistant coating for paper substrate and anti-corrosion coating materials. Additionally, corn oil can be used in pharmaceuticals; however, further refining DCO is required to meet pharmaceutical grade.

DCO and corn germ oil are extracted from different feedstock, so the composition of corn oil varies across extraction methods. Specifically, DCO generally has higher free fatty acids, phytosterols, carotenoids, and oxidative stability and lower tocopherols than corn germ oil. Nevertheless, DCO is not for human consumption. Hence, refining DCO by neutralization and other refining processes may provide the potential for various applications. While the free fatty acid content in unrefined DCO ranges between less

than 2% and 18%, refined DCO should have free fatty acid content of 1% or less by weight. In addition, a food-grade refined DCO should have less than 0.05% free fatty acids. Nonetheless, the product created from refining DCO will be different from that created with refined corn germ oil.

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 \$1.5 billion in gross domestic product annually. According to current labor market analysis, as of 2021, the manufacturing industry in Cedar Rapids employs roughly 20,000 individuals. 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, and vegetable oil, among others. Alongside the major primary products, there are lesser-value 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.

The Iowa State University-City of Cedar Rapids, Iowa Partnership was created to increase connections between university research and the city's agricultural, food, and bioprocessing industries. Multiple centers, such as the Center for Crops Utilization Research, the Office of Economic Development and Industry Relations, the Bioeconomy Institute, and the Center for Agricultural and Rural Development at Iowa State offer facilities and services for the commercialization of bioprocessing technologies and the development of research projects to explore pre-commercial scale projects. This report represents one of those connections, providing 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

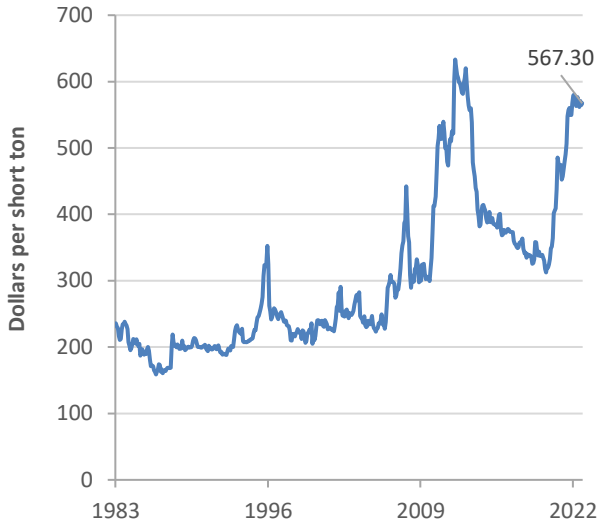


FIGURE A1 – Brewer's grits price in the Midwest.⁵

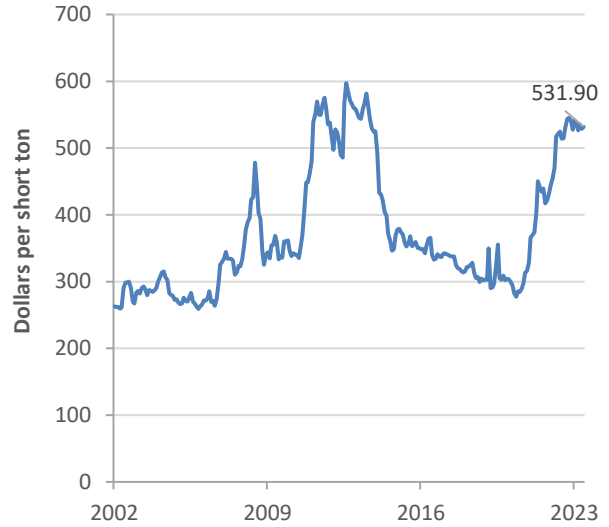


FIGURE A2 – Cornmeal price in Chicago (USDA).⁵

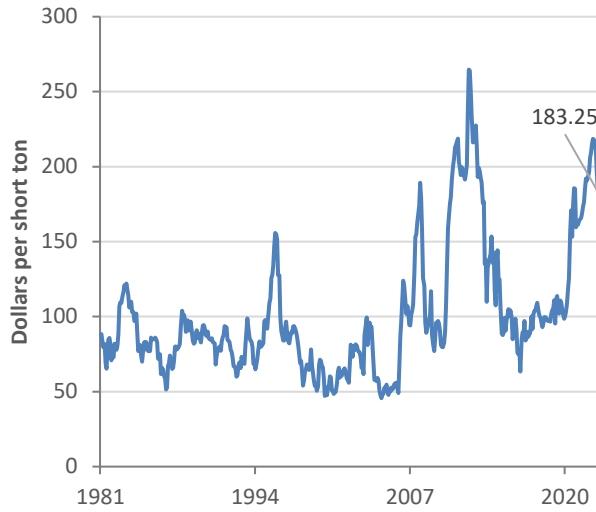


FIGURE A3 – Hominy feed price in Illinois.⁵

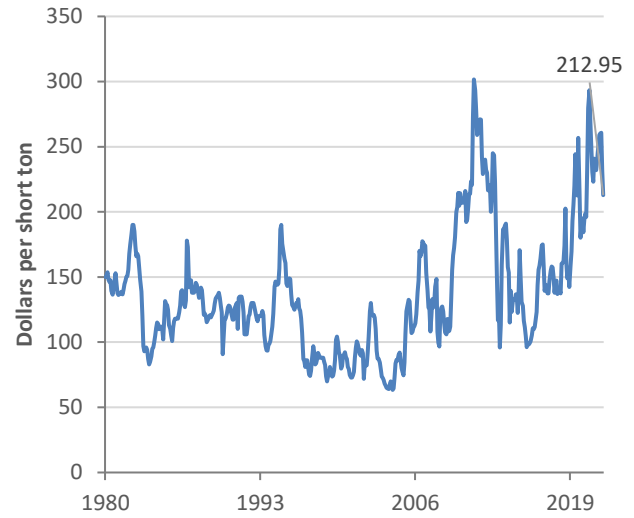


FIGURE A4 –DDGS prices: 1980-1999 Lawrenceburg, Indiana; 2000-present Central Illinois (10% moisture).⁹⁵

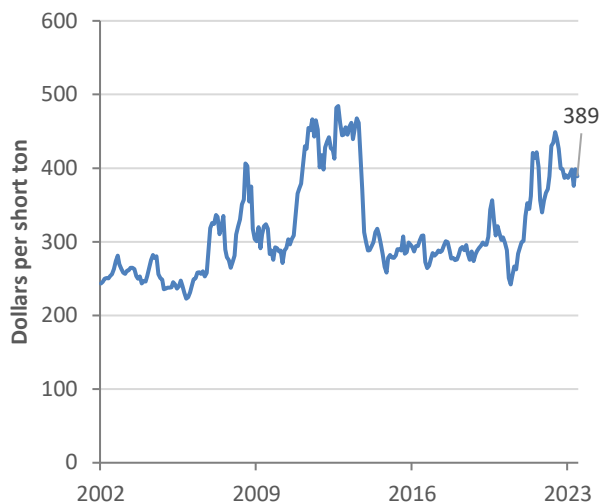


FIGURE A5 – Unrefined corn starch price in the Midwest.⁹⁶

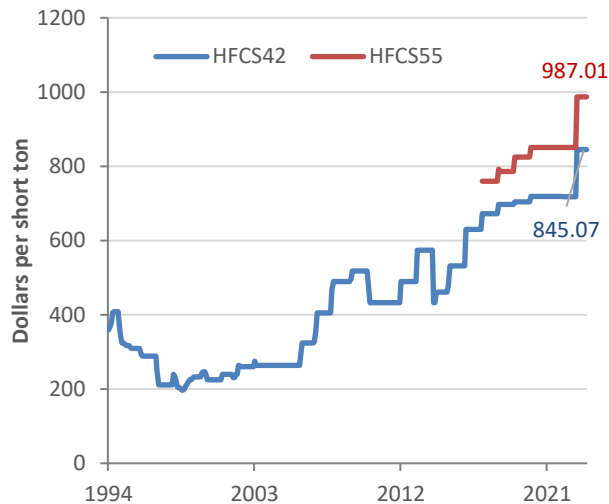


FIGURE A6 – HFCS spot and wholesale prices on a dry basis. (Multiply HFCS-42 by 0.71 and HFCS-55 by 0.77 for wet basis).⁵⁶

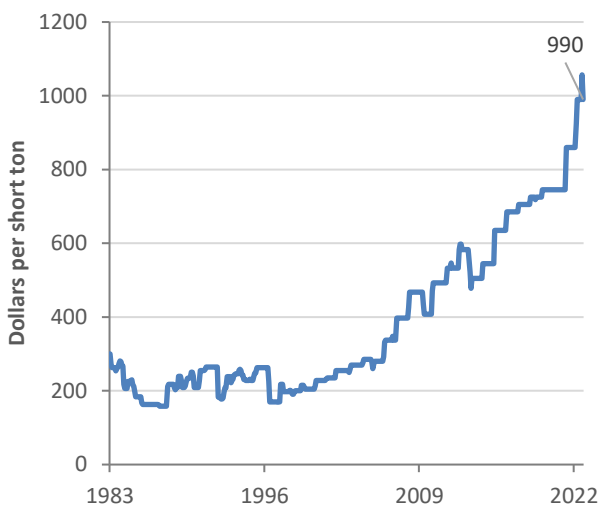


FIGURE A7 – Corn syrup price in the Midwest.⁵

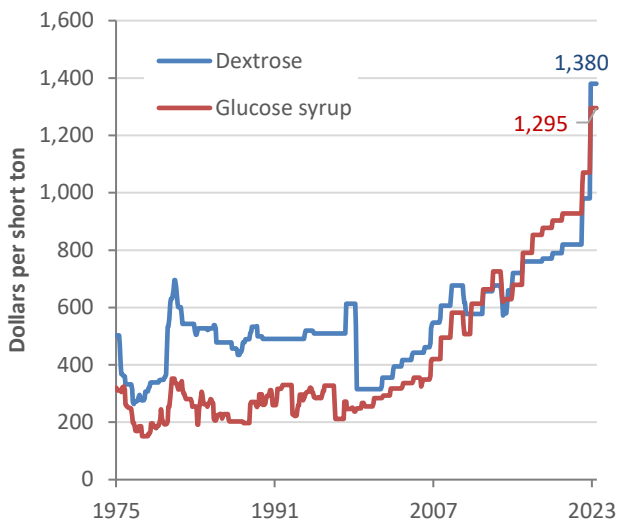


FIGURE A8 – Wholesale prices for dextrose and glucose syrup on a dry basis.⁵⁶

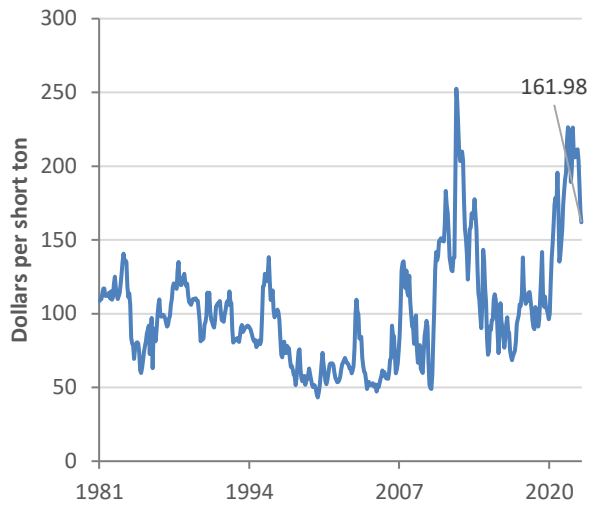


FIGURE A9 – Corn gluten feed price in the Midwest.⁵

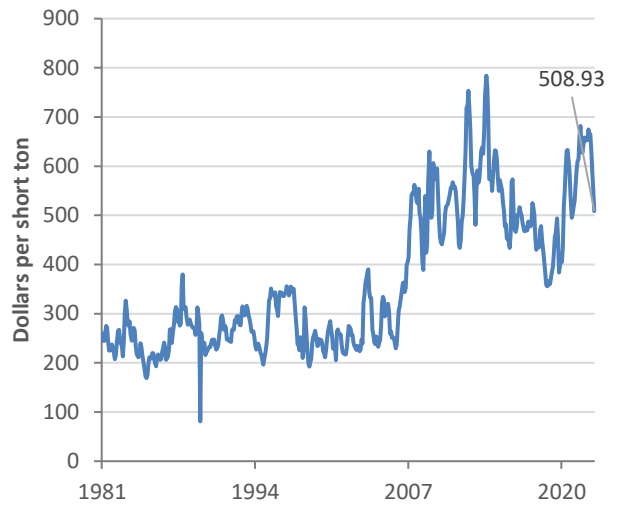


FIGURE A10 – Corn gluten meal price in the Midwest.⁵

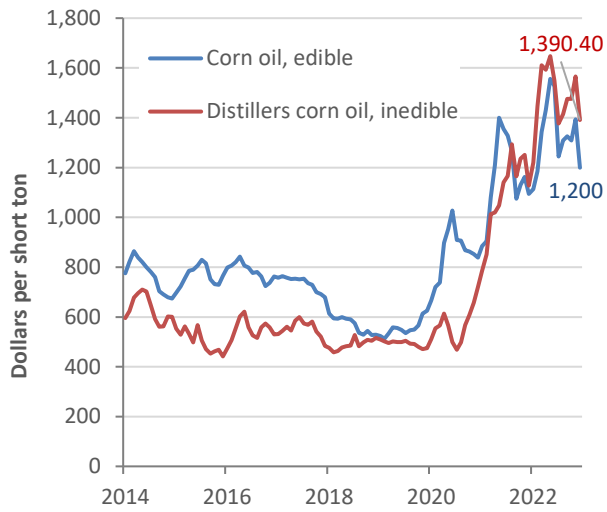


FIGURE A11 – Corn oil prices in the United States.⁵⁸

A.2 SOYBEAN PRODUCTS HISTORICAL PRICES

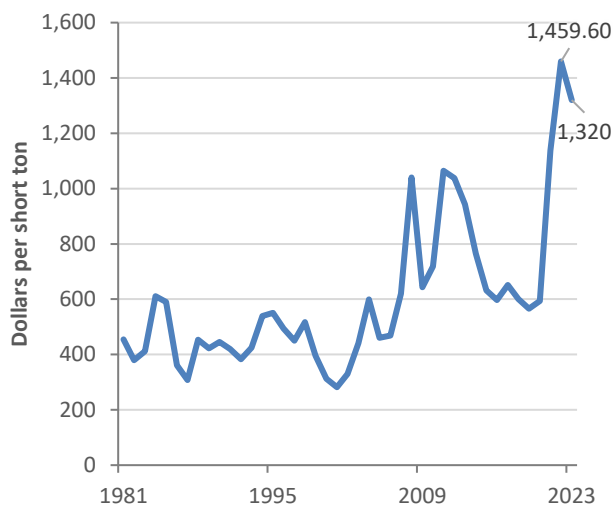


FIGURE A12 – Soybean oil price in central Illinois (annual average from September – August).⁸⁵

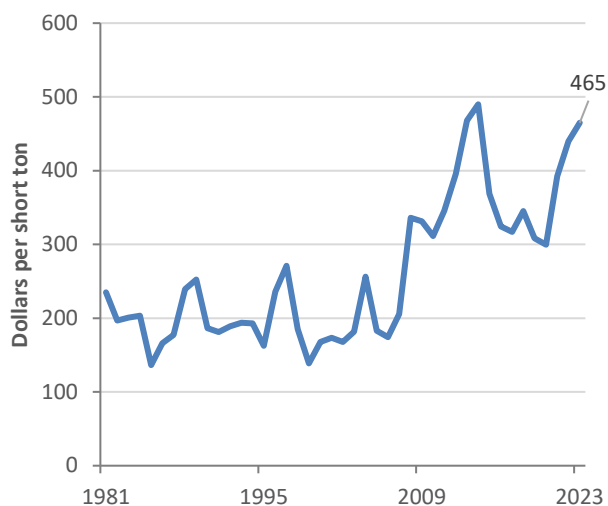


FIGURE A13 – Soybean meal price in central Illinois (annual average from September – August).⁸⁵

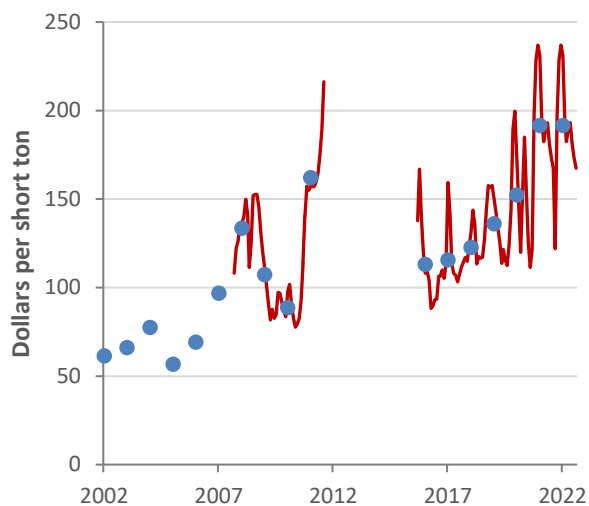


FIGURE A14 – Soybean hulls price in central Illinois. Blue circles are annual averages and orange symbols are monthly averages. Data from September 2011 to August 2015 not available.⁸⁵

A.3 CEDAR RAPIDS WASTEWATER TREATMENT PLANT DATA

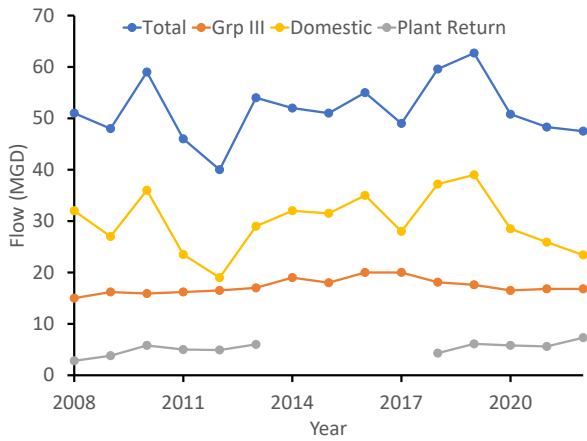


FIGURE A15 – Cedar Rapids wastewater treatment plant flow data.

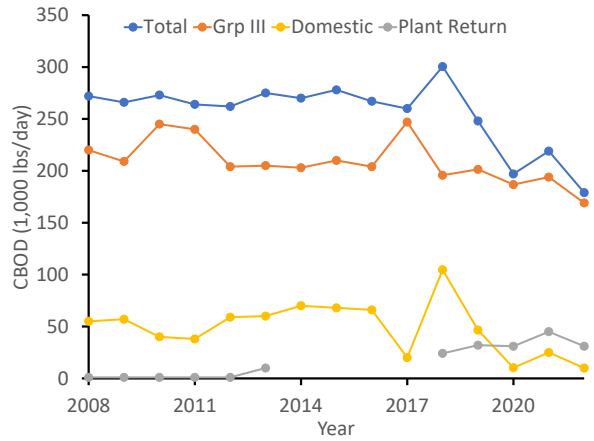


FIGURE A16 – Carbonaceous biochemical oxygen demand (CBOD) values for Cedar Rapids wastewater treatment plant.

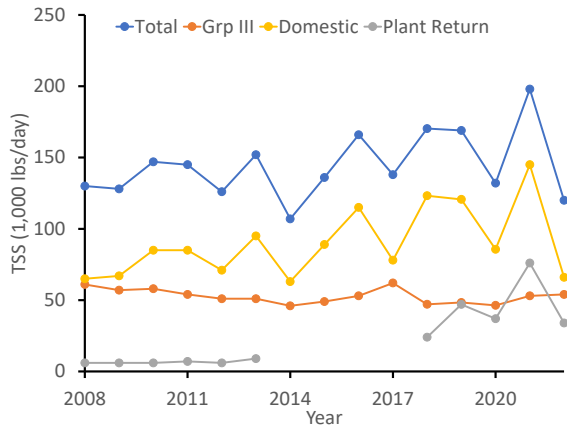


FIGURE A17 – Total suspended solids (TSS) values for Cedar Rapids wastewater treatment plant.

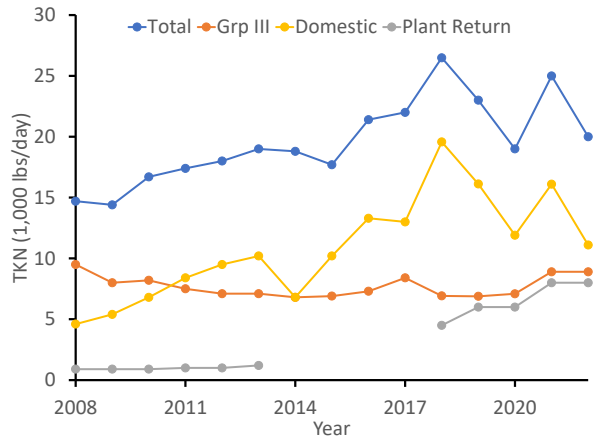


FIGURE A18 – Total Kjeldahl nitrogen (TKN) values for Cedar Rapids wastewater treatment plant.

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