Modified Dry Grind Ethanol Process

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Publication of the Agricultural Engineering Department
University of Illinois at Urbana - Champaign
UILU No. 2001-7021

July 18, 2001

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1. Introductory Material

1.1. General

Use of corn for ethanol production has grown 17 fold during the past 20 years to more than 600 million bushels per year (Figure 1). Much of the fuel ethanol production capacity in the US is concentrated in midwestern states that have large supplies of corn (Table 1). The demand for fuel ethanol is expanding due to environmental concerns and the Clean Air Act amendment of 1990, which requires the use of oxygenated fuel and reformulated gasoline to reduce carbon monoxide and other pollutants. The addition of oxygen to the fuel promotes efficient combustion and reduces tailpipe carbon monoxide (CO) emissions. Using a 10% blended gasoline fuel may reduce automobile CO emissions as much as 25%.

Corn processing for ethanol production has been accomplished both by wet milling and dry grinding. The dry grind process has a lower capital investment but suffers from low coproduct value. In the dry grind process, corn is not separated into individual fractions; whole corn is processed for ethanol production. As a result, nonfermentables, such as germ, protein, vitamins, minerals and fiber are carried through the fermentation process. These nonfermentables are recovered as animal foodstuffs, commonly known as distiller's dried grains with solubles (DDGS), which returns only 45% the value of raw corn. New technology, focusing on coproduct recovery, has potential to reduce ethanol production costs even more.

The energy required to produce a gallon of ethanol has been reduced by 50% since the late 1970s. At this time, there is a 34% net energy gain from the farmer's field to the finished liter (Shapouri et al 1996). Since ethanol production from corn has become more important during the past 30 years, many technological advances have been made in the fermentation and distillation steps of ethanol production. Currently, the largest barrier to low cost ethanol production is the value of coproducts resulting from the process. To that end, a method for germ recovery has been developed (Singh 1994; Singh 1998; Singh and Eckhoff 1996; Singh and Eckhoff 1997). Also, a method for fiber recovery has been established (Singh et al 1999a; Wahjudi 2001; Wahjudi et al 1999; Wahjudi et al 2000). These new methodologies should result in large improvements to the profitability of the ethanol industry.

1.2. The Carbon Cycle

Depicted in Figure 2 is an example carbon cycle. As a result of ethanol being from a renewable resource, it is a transportation fuel that helps reduce carbon dioxide (CO_2) emissions. In a report from the Argonne National Laboratory, they concluded that ethanol produced from corn (E95) reduces fossil energy use by 42 to 44% and greenhouse gases by 19 to 24%, compared with conventional gasoline (Renewable Fuels Association 1999). In this full fuel cycle evaluation, they included the energy necessary to grow and harvest the plant material, distill it into ethanol and transport the ethanol to gasoline terminals.

1.3. Coproducts

Coproducts are manufactured in parallel with the primary product in many food processes. Many coproducts have low value and limited markets, thus impeding profitability and sustainability of the overall process. Increasing quality of coproducts involves two efforts: understanding and controlling raw material properties and developing innovative methods to utilize all materials entering the process. Economic and regulatory pressures and a growing population will require food processing designs to maximize coproduct value while resulting in zero emissions from the process. Solids not recovered as primary product or coproducts eventually become wastewater and must be treated and disposed of at a cost to the processor. Treated wastewater from most food processes, including corn processes, contain protein, vitamins and minerals which are potential food sources to animals. Therefore, wastewater reflects lost product or coproduct. Diverting lipid, protein and vitamins prior to fermentation will provide salable coproducts. The germ meal, residue left after oil extraction, is a valuable animal food ingredient used widely in cattle diets.

Currently, the US corn to ethanol industry consumes approximately 600 million bushels of corn per year (Office of Chief Economist 2001). Approximately 40% of the current corn to ethanol capacity is from the dry grind ethanol process. Ethanol is produced in the dry grind ethanol process by grinding whole corn and placing all corn solids in the fermentor.

1.4. The Corn Kernel

Kernel composition forms the basis for all corn processes (Figure 3). Germ contains all material necessary to form a new corn plant, including a variety of enzymes and micronutrients needed for the growth of the germinating embryo. Endosperm is the largest component of the kernel and contains primarily starch and protein. It can be divided into two areas, hard and soft endosperm. The ratio of these two types of endosperm is affected by hybrid and growing condition. Soft endosperm regions are the easiest to mill and have higher concentrations of starch. The purpose of the endosperm is to provide energy to the newly germinated embryo (germ). Pericarp functions to protect the kernel from mold and abrasion and often is referred to as the “hull” or “bran” of the kernel. It consists of cellulose, hemicellulose and lignin, collectively referred to as “fiber”. The tip cap is the location of attachment of the kernel to the cob. While in the field, this is the pathway where water and other nutrients entered the kernel. Most of the water and other chemicals used during processing enter through the tip cap.

Corn is the most genetically diverse crop cultivated in the world. It is easily hybridized to create new, unique hybrids that can be commercialized rapidly. Using biotechnology, we have developed methods that further speed up changes to the kernel’s genetic composition, opening more opportunities for new products from corn and corn processes. The corn plant also has the unique capability to generate large amounts of crop on a per unit area basis, with yields over 200 bushels per acre now possible.

1.5. Functional Foods

When the Dietary Supplement Health and Education Act of 1994 was passed, the regulation of dietary supplements was altered drastically. This law permits the marketing of ‘dietary supplements’ with less regulatory oversight than required for food additives and drugs. As many functional foods are naturally occurring in foods consumed as part of the normal diet, the opportunity to identify those in corn is timely. With the modified dry grind corn processing plants to produce multiple products, lipid soluble compounds will be available in the germ portion. Also, compounds held within the normal fibrous structures can be extricated and utilized.

Functional foods are foods that, by virtue of physiologically active food components, provide health benefits beyond basic nutrition. We are now finding that plants which traditionally have been part of food chain contain bioactive components not hitherto recognized for their physiological effects beyond that of basic nutrition. Because corn kernel composition is changed readily through conventional hybridization and biotechnology methods, the kernel may become a significant source of these bioactive components. Therefore, we will be at the forefront in identifying and isolating those compounds from corn, a worldwide accepted food for human beings and animals.

To date, functional foods research has tended to focus on single bioactive components which can be extracted, tabletized and used as dietary supplements. However, there likely are additional unrecognized components within the food which may enhance, or mask, the potency or bioavailability of the identified bioactive components.

1.6. Value Enhanced Corn

Corn with particular characteristics that provide added value for one or more end users is value enhanced. Examples of value enhanced corn are white, waxy, high amylose, high oil, hard endosperm (for flaking) and high lysine. Other items for consideration are low stress cracks, organically grown and postharvest pesticide free. Some characteristics which could be introduced are: high stearic acid, high oleic acid, high linoleic acid, cholesterol reducing compounds, anticancer compounds and starch extractability.

2. Corn Production and Use

2.1. World Corn Production

World corn production (Table 2) is primarily in the US and China, as is consumption (Table 3). During the past five years, production and consumption have remained relatively stable. The five countries producing the most corn are US, China, EU, Brazil, Mexico and Argentina; whereas, consumption is primarily in the US, China, EU, Brazil, Mexico and Japan.

2.2. US Corn Production

Even though the acres of corn planted in the US have remained relatively constant during the past several decades, there has been an increase in overall production due to higher yields per unit of land (USDA 2001). Depicted in Table 4 are US corn production, yield and area harvested. The five states with the largest production (Table 5) are the central states of the corn belt. Those states with the highest yields per unit of land actually produce a small amount of the total production (Table 6); however, it is important to recognize that irrigated lands are important sources of production.

2.3. US Corn Use for Food and Industrial Uses

During the past twenty years (ERS, USDA 2001), US corn consumption (Table 7) has increased for use as fuel alcohol, high fructose corn syrup, glucose, starch and beverage alcohol by approximately 1700, 250, 40, 70 and 60 per cent, respectively (Figure 4). In the US, consumption of corn as foodstuffs for animals and human beings continues to encompass the largest portion of corn production. Projections by the Office of the Chief Economist (2001) for US corn use for ethanol are 730 and 740 million bushels per year for 2009 and 2010, respectively.

3. Corn Processing

3.1. Introduction

There are three corn processes commercially in use today: dry grind ethanol, corn wet milling and dry milling. Of these three, dry grind ethanol and corn wet milling are used to produce ethanol from corn. A fourth process, modified dry grind ethanol, is a recently developed process using a combination of dry grind ethanol and corn wet milling methodology. All four processes generate an array of coproducts (Table 8) that have varying degrees of separation of the corn kernel's constituents of starch, protein, fiber and oil. For the purposes of ethanol production, dry grind ethanol, modified dry grind ethanol and corn wet milling processes yield slightly different amounts of ethanol and different types and levels of coproducts that can be used as animal food ingredients (Table 9).

3.2. Dry Grind Ethanol

The conventional dry grind ethanol process is designed to ferment as much of the corn kernel as possible. In the dry grind ethanol process, whole corn first is ground and then cooked with enzyme added to reduce viscosity of the cooked material. The starch in the cooked "mash" is converted to glucose with enzymes. The mash is fermented and distilled to produce ethanol, distillers dried grains with solubles (DDGS) and carbon dioxide. Dry grind ethanol has lower capital costs than corn wet milling but does not have as high coproduct value (Table 10, Figure 5). A 100,000 bu/day processing facility will cost $75 to 80 million to build. A typical 35,000 bu per day processing facility will cost $30 million to construct in the US. Dry grind ethanol processes are usually smaller scale than wet milling; typically DDGS is sold directly as a wet animal food. Historically, dry grind ethanol plants supplied ethanol for beverage and industrial uses.

Since the 1970's energy crisis in the US, dry grind has played an increasing role in supplying fuel grade ethanol. The Clean Air Act requires that auto fuel contain oxygen to reduce CO and ozone in ozone nonattainment areas. A 10% mixture of ethanol with gasoline meets these regulatory standards. Ethanol competes with methyl tertiary butyl ether (MTBE) which has been connected with groundwater pollution in several areas of the US. Unlike MTBE, ethanol is biodegradable should it be released into the groundwater.

The five basic steps in the conventional dry grind ethanol process are grinding, cooking, liquefaction, saccharification and fermentation (Figure 6). This process has a relatively low capital cost but suffers from production of low value coproducts, ie, distiller's dried grain with solubles (DDGS). In the dry grind process, the whole kernel is ground, using a mill, to facilitate water penetration in the cooking process. The two types of mills used are hammermills (kernel breakdown results from collision of corn with the hammers) and roller mills (a pair of rolls exert a compressive force by operating the rolls at different speeds).

The milled corn is mixed with water, making 22 gallons of mash from a bushel of corn (Singh 1998). After cooking at 320°F, mash is cooled to 145°F and mixed with fungal amylase. The mixture is transferred to saccharification reactors, maintained at 140°F, where starch is converted to fermentable sugars. Converted mash is cooled to 84°F and fed to fermentation reactors where fermentable sugars are converted to ethanol and CO_2.

$C_6H_{12}O_6$ + H_2O + Yeast →	2 CO_2 +	2 C_2H_5OH + H_2O +	Heat
Glucose	*Carbon Dioxide*	*Ethanol*	*BTU*
100 lb	48.8 lb	51.1 lb	17,000 BTU

The resulting beer is flashed to separate the carbon dioxide. The resulting liquid is fed to a recovery system consisting of two distillation columns and a stripping column. The 95% ethanol stream (neat beer) is transferred to a molecular sieve where the remaining water is removed using adsorption technology. Purified ethanol, denatured with a small amount of gasoline, produces fuel grade ethanol. Another product is produced by distilling 95% ethanol to remove impurities, resulting in 99.95% ethanol for nonfuel uses.

Whole stillage withdrawn from the bottom of the distillation unit is centrifuged to produce distillers grains and thin stillage. Using an evaporator, thin stillage is concentrated to form distillers solubles, which is added to the distillers grains process stream and dried to 88% dry matter. This product is marketed as distillers dried grains with solubles (DDGS).

3.3. Modified Dry Grind Ethanol

During the 1990s, University of Illinois researchers developed a modified dry grind ethanol process to increase the value and quantity of coproducts made from a dry grind ethanol process. Technologies conventionally used in the wet milling process are used to remove germ and fiber after a short soaking step (Figure 7) prior to a conventional dry grind ethanol process. Thus, two sets of well established unit operations are joined together in a new process to obtain more and higher valued coproducts during ethanol production.

In the modified dry grind ethanol process, whole corn is soaked in water and lightly ground in a conventional Bauer mill. Germ and fiber are recovered using conventional hydrocyclone technology used in the corn wet milling industry. This process separates the germ (Singh and Eckhoff 1997) and fiber (Wahjudi et al 2000) using the principles of density difference and hydrodynamics; germ and fiber are lighter after soaking and flow out the overflow of the hydrocyclone, while the starch and protein flow out the underflow. Germ and fiber are washed, dewatered and dried; fiber is aspirated to separate fiber and germ.

Because much of the germ and fiber consist of materials that are not fermentable into ethanol, efficiency of the overall process is improved over conventional dry grind ethanol. While overall capital costs are higher for modified dry grind ethanol compared to conventional dry grind ethanol, they are still much lower than corn wet milling. This allows smaller processing facilities to be built and operated economically, which can be located strategically near corn producing regions.

Germ recovered from this process is of a quality that can be used for oil extraction and contains 45% oil (dry basis), similar to oil content found in germ recovered using corn wet milling (Singh and Eckhoff 1997). This ability to recover high purity germ alleviates a problem with germ recovered by other processes. Because oil extraction is a capital intensive process, the economy of scale is large. Germ that is not of high purity cannot be accepted at these large extraction facilities, which greatly reduces the value of lower purity germ. Ability to recover high quality germ as a coproduct is a distinct and important advantage of the modified dry grind ethanol process.

In work done with our collaborators at the Eastern Regional Research Center, Agricultural Research Service, United States Department of Agriculture, it has been shown that fiber recovered in a modified dry grind ethanol process contains naturally occurring nutraceutical compounds that reduce serum cholesterol (Moreau et al 1999).

The amount of nonfermentable solids in the fermenter is reduced, increasing the amount of material that can be processed by a facility. Savings for using the combined germ and fiber removal process over conventional dry grind ethanol are estimated at 5 to 7 cents per gallon (Taylor et al 2001). Costs of retrofitting a 35,000 bu per day dry grind plant with germ and fiber removal technology are estimated at $11 million.

The largest improvement in processing efficiency of the modified dry grind ethanol process over conventional dry grind ethanol is removal of nonfermentable material prior to fermentation. A second major benefit is decreased capital and operating costs in the evaporation step when concentrating thin stillage. We believe modified dry grind ethanol to be the most profitable and sustainable process for ethanol production over varying market conditions.

3.3.1. Germ Recovery in the Modified Dry Grind Ethanol Process

The germ recovery process will lower feedstock costs in ethanol production by increasing the value of coproducts recovered in the dry grind process (Table 11). The germ recovery process involves soaking whole corn in water for 3 to 12 hours, at 140°F, before conventional wet milling degermination and germ recovery (Singh and Eckhoff 1996). Soaking of whole kernels results in differential swelling of corn components which loosens the attachment of the various grain components to one another. After soaking the corn, a conventional Bauer mill is used for degermination, as is used in wet milling. The germ is recovered by using a system of conventional germ hydrocyclones and the remainder of the corn is ground wet.

Recovery of the germ as a coproduct opens up options and economic opportunities for the dry grind ethanol processor. Based on historical data from 1991 to 2000, crude corn oil from germ has a higher value of $0.246 per lb as a coproduct than the $0.06 to 0.09 per lb from DDGS (Table 10, Figure 5). Recovery of germ allows additional processing of the germ to extract corn oil which has many higher value uses (Table 12). Additionally, there are cost savings associated with increased fermentor capacity due to removal of nonfermentables from the corn mash and due to reduced fouling of the thin stillage evaporators (Singh et al 1999b).

3.3.2. Fiber Recovery in the Modified Dry Grind Ethanol Process

The fiber recovery process has several advantages compared with the conventional dry grind ethanol process. It increases fermentor capacity 6 to 8 %. The concentration of protein in DDGS is increased as fiber is decreased and enhances the potential for including DDGS in nonruminant livestock diets. Swine and poultry require lower fiber diets relative to cattle. These industries have been growing relative to the cattle industry and thus have created strong demand for ingredients such as a modified DDGS coproduct.

In comparison to other cereal grains, high levels of cholesterol lowering phytosterol components, ferulate phytosterol esters (FPE), free phytosterol and phytosterol fatty acyl esters, can be extracted from pericarp fiber (Moreau et al 1999). Compared with other cholesterol lowering edible oil supplements, corn fiber oil extracted from corn fiber has several advantages. It is the only product that contains three different classes of natural cholesterol lowering compounds (FPE, free phytosterol and fatty acyl phytosterol esters). Compared to other grain fibers, corn fiber contains relatively high amounts of these phytosterol compounds. Moreover, in mammals these phytosterol compounds are esterified to ferulic acid that has antioxidant properties. These cholesterol lowering compounds can be used as nutraceuticals and command a high value in the market.

3.4. Corn Wet Milling

Corn wet milling accounts for 55 to 60% of the total ethanol produced in the US (Rendleman and Hohmann 1993). Wet milling is performed primarily to isolate and recover starch, which can be used to produce food grade modified and unmodified starches, glucose syrup, high fructose corn syrup, ethanol and other chemicals via fermentation. For production of ethanol, corn wet milling processors ferment starch refined from the corn kernel. The corn wet milling process results in corn separation into four components, ie, starch, germ, fiber and protein. There are five basic steps to achieve corn component separation, ie, steeping, germ recovery, fiber recovery, protein recovery and starch washing (Figure 8).

Corn wet milling is a relatively complex process, with higher capital investment and thus larger economy of scale. Processing plants are 100,000 to 400,000 bushels per day and run nearly 365 days per year. A 100,000 bushels per day (85 million gallons ethanol per year) corn wet milling facility will cost $250 to 300 million to build. Historically, wet milling provided pure starch products (>99.5%) for the paper and corrugating industries, modified starches for food ingredients and eventually high fructose corn syrup (HFCS). By the late 1970s, the US corn wet milling industry was growing at a rapid pace to supply HFCS to the beverage market. As the HFCS market matured, emphasis was placed on ethanol production. Demand for HFCS in recent years has been supported by growth in Mexico. However, high capital costs of the process make expansion in this segment more economically risky than dry grind ethanol production.

The wet milling process begins by steeping corn in a solution of weak sulfurous acid for 24 to 48 hours in a semicontinuous steeping system that hydrates and softens the kernel and leaches solubles from the germ (Figure 8). Steeping is a biochemical, chemical and mechanical process where the corn kernel is prepared for processing. Starch quality and quantity and coproduct components depend on the steeping process. During steeping, corn is soaked in 50 to 52°C water, where the kernels absorb water, increasing the water content from 15 to 45%. Sulfur dioxide (SO_2) is introduced (1,500 to 2,000 ppm) in the latter stages of the steeping process to prevent bacterial growth and loosen the disulfide bonds within the protein matrix surrounding the starch granules. Steeping is partly a biological process, since lactic acid is involved to create an acidic environment which is desirable for SO_2 activity in disintegrating the endosperm protein matrix. Water uptake by the corn kernel is enhanced when SO_2 and lactic acid are present together.

The resulting starch is processed through cooking, liquefaction, saccharification and fermentation. The broth is passed through a distillation unit to separate ethanol from water and other soluble solids. Nutrients remaining after fermentation are used as animal food ingredients. Carbon dioxide from the fermentation process also may be marketed.

Wet milling is more capital intensive and requires a knowledge base in the art of wet milling. However, the wet milling process has a major advantage in producing high value coproducts, eg, germ, corn gluten meal (CGM) and corn gluten feed (CGF), which is applicable to offsetting the initial capital cost.

3.5. Dry Milling

Corn dry milling is primarily a physical separation process of corn components. The products from this process are not as highly concentrated in starch, protein, fiber and oil as the corn wet milling process. The phrase "dry milling" often is used to describe the dry grind ethanol process, creating confusion. The dry milling process begins by adding a small amount of water to the corn kernel, increasing moisture 22%. This causes differential swelling of the germ relative to the other kernel components and increases resiliency of the germ. Corn is sent through an abrasion step that breaks apart the kernel into pericarp, germ and endosperm fragments. A combination of steps follows to remove pericarp and germ from the endosperm. Aspiration is used to remove pericarp fragments by air separation. A gravity table typically is used to separate germ and germ pieces from the remaining endosperm. Separation of corn constituents is not perfect; a small fraction of the pericarp and endosperm remains attached to the germ and, therefore, lowers the concentration of corn oil in the germ fraction. Germ obtained from dry milling, due to its lower concentration of oil compared to germ from wet milling, is not accepted for processing by the corn oil extraction and refining industry.

Endosperm products are separated by a series of size separation steps. The premium product of dry milling is the flaking grits, widely used in breakfast cereals, which consist of large pieces of endosperm. Smaller classifications of endosperm particles make up milling products such as brewers grits, cones, meal and flour. These are used in a variety of human foods, such as snack and bakery foods. The germ and pericarp fractions are sold as animal food ingredients.

4. A Modified Dry Grind Ethanol Facility

4.1. Overview of Proposed Facility

The proposed plant would use the modified dry grind ethanol process, allowing the removal of germ and fiber as coproducts and giving the facility a broader array of coproducts relative to a conventional dry grind ethanol process (Figure 7). The modified dry grind ethanol process results in ethanol, high quality germ and fiber coproducts and an animal food coproduct. A larger array of high quality coproducts will make the modified dry grind ethanol facility more robust under varying economic conditions, relative to conventional dry grind ethanol and corn wet milling. The proposed plant would have a grind capacity of 40,000 bushels per day or 14 million bushels per year and produce 35 million gallons of fuel grade ethanol per year along with multiple coproducts (Table 13). The plant would operate approximately 350 days per year, allowing some down time for plant maintenance. Total capital investment to build the plant in the Midwest is estimated at $49 million, including equipment costs and working and startup capital investments.

4.2. Raw Materials and Facility Location

4.2.1. Overview

It is estimated that 14 million bushels of corn will be needed annually to supply the proposed facility, based on annual operation of 350 days. Based on an average corn crop yield of 130 bushels per acre approximately 108,000 acres of crop land will be needed to supply the facility. An adequate infrastructure using two or more modes of transportation (eg, roads, navigable rivers and rail) will be needed to reliably and economically transport the corn to the facility. For the facility to have the largest opportunity for successful long term operation, location of the site is very important.

4.2.2. Water and Wastewater Treatment Requirements

With use of modern technology, water requirements have been reduced during the past 10 to 15 years. Water reuse and recycling have become commonplace in the ethanol industry. Approximately 10 years ago, more than 20 gallons of water were needed to process each bushel of corn for ethanol production. Today, most plants in the US require less than 7 gallons per bushel of corn processed. In many plants, the only losses of water during processing are due to boiler blow down and evaporative losses from cooling towers (Bryan and Bryan 2001). With the modified dry grind ethanol process, water requirements are not increased greatly over requirements of conventional dry grind ethanol. This is due to the ability to reuse the soak water in the hydrocyclone and fermentation portions of the process.

However, a sufficient, economical and reliable supply of fresh water is needed for operation of the facility. For the proposed plant, 300,000 gallons of water per day are needed. This may be too large a quantity for some municipalities to supply, should a facility be built in their district. Even if the local municipal government can supply these quantities, the costs may be unattractive. Personnel involved in planning the new facility should consider drilling their own wells, but the actual availability and quality of the water should be investigated thoroughly. Regardless of the source of water, high mineral content is a concern, as it leads to higher maintenance costs throughout the plant.

Although some US plants are now considered "zero" discharge, treatment of wastewater and available treatment options should be investigated prior to location of a facility. A local municipal treatment facility may be able to handle the effluent from the facility, but distance from the facility or treatment costs may pose problems.

4.2.3. Energy

While energy needs for ethanol production have decreased during the past 30 years, purchase of economical and reliable energy sources are essential to stable operation of the facility. Placing an emphasis to conserve energy at the facility will reduce the burden on natural resources and the surrounding community. Proximity to a sufficient supply of energy, such as natural gas, coal, electricity and petroleum must be considered. The ability to utilize more than one source of energy may be necessary, as well as relative costs of each source.

4.3. Facility Output: Ethanol and Coproducts

At an annual corn grind rate of 12.5 million bushels, the modified dry grind ethanol plant would produce 31 million gallons of ethanol, 42.6, 47.6 and 97.6 million pounds of germ, fiber and dried stillage material (modified DDGS), respectively. The processor is anticipated to sell germ, fiber and modified DDGS as coproducts to generate revenue. The germ product would contain 44 to 45% oil and could be extracted by another process to yield 18.7 and 23.9 million pounds of corn oil and germ meal, respectively. The fiber product, containing 2% corn fiber oil, could be used to extract 1.0 million pounds of corn fiber oil annually. Relative product values are shown in Table 11. Extractions of germ oil and corn fiber oil are not expected to be carried out at the facility.

4.4. Economic Analysis

4.4.1. Conventional Dry Grind Process

Current estimated total costs for erecting a conventional dry grind ethanol plant producing approximately 30 million gallons of ethanol per year would be $38,000,000 (Table 14). The rate of pay back on the capital investment for a conventional dry grind ethanol facility is estimated at 4.0 years and generate an estimated net income of $9.5 million annually. Based upon a daily grind rate of 33,400 bushels of corn, with 350 days of operation per year, the facility would require 11.7 million bushels of corn annually. With an estimated yield of 2.6 gallons of ethanol per bushel, the plant would produce 30 million gallons annually. With 15 lb of DDGS produced per bushel, a conventional dry grind process would generate 175 million pounds (87,500 tons) of DDGS per year worth $10.6 million.

4.4.2. Recovery of Germ

At the proposed facility, we would use the modified dry grind ethanol process to recover both germ and fiber since there are several advantages compared to conventional dry grind ethanol and corn wet milling processes. Overall, the modified dry grind ethanol process requires less capital investment than corn wet milling. The germ coproduct removed during the modified dry grind ethanol process is of similar quality to germ obtained from corn wet milling, allowing the processor to sell germ to corn oil refineries. Recovery of germ by the modified dry grind ethanol process increases capacity of fermentors, allowing higher corn grinding and ethanol production rates.

The quick germ process provides an important economic advantage for retrofitted dry grind ethanol plants. One direct economic benefit of the quick germ process is the recovery of germ as a valuable coproduct. For a 40,000 bushel per day modified dry grind ethanol plant, germ recovery contributes approximately 5 to 7 cents per gallon of ethanol produced (Taylor et al 2001b). Approximately 12% of the savings come from the sale of germ as a new coproduct and 88% from the increased grind rate due to removal of germ and increased production of ethanol. Savings achieved due to extra ethanol production depends on the extra capacity at the stripping and the coproduct handling facilities in the plant. These savings do not include the savings associated with: 1) reduced fouling of the thin stillage evaporator (heat transfer equipment) and, therefore, savings in capital, energy and maintenance costs and 2) increase in value of the modified DDGS coproduct due to increased protein content. Conventionally produced DDGS in the US currently is marketed based on protein content; therefore, an increase in protein content of modified DDGS would increase market value. Singh and Eckhoff (1997) showed that retrofitting a 35,000 bu/day conventional dry grind ethanol plant with a germ recovery process would cost approximately $6 to 9 million with a payback period of 1.9 years.

4.4.3. Recovery of Fiber

Recovery of fiber in the modified dry grind ethanol process presents additional advantages. Fiber recovery uses the same equipment as used for germ recovery and also increases fermentor capacity. The corn fiber oil in the recovered fiber contains nutraceutical compounds valued at $0.80 to 1.00 per lb. Recovery of fiber would be most profitable if used in conjunction with a germ recovery process. The germ and fiber can be recovered by floatation simultaneously with slight changes in the specific gravity in the first grind tank (Singh et al 1999). If the fiber recovery process is used in conjunction with germ recovery, the additional amount of capital required for fiber recovery portion of the process is approximately $1.5 to 2.0 million. Most of this capital is associated with increase in screening, dewatering and drying facilities. This capital is in addition to capital required for germ recovery. Recovery of fiber would increase further the grind rate of the facility and, therefore, will increase the amount of ethanol produced. Total protein content in modified DDGS would increase due to recovery of fiber. The fiber coproduct can be used for recovery of corn fiber oil and high valued nutraceutical compounds. At present, it is difficult to estimate the value of the corn fiber oil; however, products similar to corn fiber oil currently are priced at $2 to 5 per lb (retail values) in US markets.

Assuming a modest selling price of 9 cents per lb for germ (based on the historical average) and 2 cents per lb for fiber the payback period of a retrofitted dry grind ethanol plant was found to be 2.4 years (Wahjudi 2000). This analysis did not incorporate increased DDGS market value and reduced energy and maintenance costs from reduced fouling of heat transfer equipment. Incorporating these costs would reduce further the payback period.

4.4.4. Combined Germ and Fiber Recovery — Analysis and Benefits

Estimated capital and revenue generated by modified dry grind ethanol process are shown in Table 15 with annual net income greater than $11 million. These estimates do not take into consideration the additional benefit of reduced evaporator capital and operating costs. Evaporators are used to concentrate the thin stillage process stream prior to being mixed with distillers grains to form DDGS. In conventional dry grind ethanol, these evaporators represent the most capital and energy intensive step in the overall process. Due to components present in the germ and fiber, the evaporators have surface buildup called fouling. This requires the evaporators to be taken off line regularly for cleaning and maintenance. Regular maintenance reduces the effective capacity of each evaporator, requiring process facilities to over design their evaporation capabilities, resulting in large increases in capital investment.

Recovery of germ and fiber in the modified dry grind ethanol process also improves the value of the modified DDGS coproduct. By recovering germ and fiber, the percent protein in modified DDGS is increased and total fiber content reduced, making the coproduct more valuable as an animal food ingredient. Conventional DDGS can be fed in limited quantities to non-ruminant animals. Higher percent protein and lower percent fiber in the modified DDGS should allow this coproduct to be fed to swine and poultry animals at higher levels than conventional DDGS.

We have presented two scenarios for the modified dry grind ethanol process. The first used an average price for crude corn oil for a 10 year period 1991 to 2000. The second used crude corn oil data for the first part of 2001, a period of unusually low prices. For all scenarios (conventional dry grind, modified dry grind with historical germ price and current germ price), the cost of corn was held constant at $2.30 per bushel.

For modified dry grind ethanol scenarios (Tables 15 and 16), the yield of ethanol was estimated to be similar to the yield for corn wet milling at 2.5 gallons of ethanol per bushel. This may be a conservative yield estimate for the modified dry grind ethanol process. Based on recent research on fermentor capacity (Taylor et al 2001a, b), the modified dry grind ethanol process was assumed to have a 7% higher grind rate (35,700 bu/day) than the conventional dry grind ethanol process (33,400 bu/day). The value of recovered fiber was estimated at $0.018 per pound, a low value, since the market for this new coproduct is undetermined.

Germ price was estimated by making two assumptions for the marketing germ. First, recovered germ was considered to have 40% oil content. This is a conservatively low estimate of oil content based on previous research (Singh 1994, Singh and Eckhoff 1997, Singh and Eckhoff 1996). Second, the value of extracted germ meal would be offset by the crushing margin costs. When selling germ to an oil extraction facility, corn processors receive a credit for the germ meal, which is the germ material remaining after oil is extracted. The oil extraction facility claims a cost for handling and extracting the oil from the germ, called the crushing margin.

In both scenarios for modified dry grind, total coproduct value and net income were higher than or similar to the conventional dry grind process. Total coproduct value was $14.4 and $12.3 million for the historical and current germ price scenarios, respectively, compared to $10.6 million for conventional dry grind. Net income was estimated to be $11.4 and $9.3 million for the historical and current germ price scenarios, respectively, compared to $9.5 million for conventional dry grind.

Payback period for modified and conventional dry grind ethanol processes was found to be sensitive to market prices of the respective dried grain coproduct. A decline in conventional DDGS prices would give processors stronger incentives to use the modified dry grind ethanol process. Previous workers found similar promising returns for the modified dry grind ethanol process. In fact, no research has produced data to show modified dry grind to perform less economically than conventional dry grind under the same conditions. This is because of increased fermentor capacity and higher value of coproducts of the modified process. If coproduct value can be considered to be a major factor in the sustainability of the ethanol industry, the modified dry grind ethanol process appears to have an advantage over conventional dry grind ethanol.

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6. Tables

Table 1. US ethanol production capacity, from multiple product dry grind corn processing plants.

Company	Location	mmgy*
AGP	Hastings, NE	52
Agri-Energy	Luverne, MN	17
Alchem	Grafton, ND	10.5
Al-Corn	Claremont, MN	17
Broin	Scotland, SD	7
Central Minnesota	Little Falls, MN	18
Chief Ethanol	Hastings, MN	62
Chippewa Valley	Benson, MN	20
Corn Plus	Winnebago, MN	20
DENCO	Morris, MN	15
Ethanol 2000	Bingham Lake, MN	28
Exol	Albert Lea, MN	17
Golden Triangle	Craig, MO	15
Gopher State	St. Paul, MN	15
Heartland Corn	Winthrop, MN	35
Heartland Grain	Aberdeen, SD	8
Heartland Grain	Huron, SD	14
Minnesota Energy	Buffalo Lake, MN	12
Northeast MO Grain	Macon, MO	15
Pro-Corn	Preston, MN	18
Sunrise Energy	Blairstown, IA	7
Sutherland	Sutherland, NE	15
Wyoming Ethanol	Torrington, WY	5
Total Capacity		443

* million gallons per year
Note: Total capacity, including barley, beverage waste, brewery waste, corn, milo, paper waste, potato waste, starches, sugars, waste beer, wheat, whey etc, is 1,900 million gallons per year.

Table 2. World corn production in million bushels (million tonnes).

Country	1995	1996	1997	1998	1999	2000
US	7,374 (187)	9,233 (234)	9,207 (234)	9,759 (248)	9,431 (240)	9,970 (253)
China	4,244 (108)	4,598 (117)	4,126 (105)	4,882 (124)	5,039 (128)	4,174 (106)
EU	1,131 (29)	1,336 (34)	1,489 (38)	1,342 (34)	1,457 (37)	1,511 (38)
Brazil	1,218 (31)	1,407 (36)	1,297 (33)	1,319 (33)	1,260 (32)	-- --
Mexico	629 (16)	766 (19)	727 (18)	709 (18)	748 (19)	697 (18)
Argentina	432 (11)	531 (13)	590 (15)	532 (14)	610 (15)	630 (16)
Total	19,575 (497)	22,527 (572)	22,637 (575)	23,414 (595)	23,542 (598)	23,026 (585)

Table 3. World corn consumption in million bushels (million tonnes).

Country	1995	1996	1997	1998	1999	2000*
US	7,215 (183)	7,043 (179)	7,652 (194)	7,570 (192)	7,550 (192)	7,796 (198)
China	3,914 (99)	4,535 (115)	4,806 (122)	4,616 (117)	4,722 (120)	4,725 (120)
EU			1,497 (38)	1,496 (38)	1,525 (39)	1,571 (40)
Brazil	1,442 (37)	1,462 (37)	1,368 (35)	1,348 (34)	1,317 (33)	-- --
Mexico	841 (21)	920 (23)	980 (25)	876 (22)	921 (23)	949 (24)
Japan	641 (16)	629 (16)	625 (16)	618 (16)	644 (16)	632 (16)

*estimated

Table 4. US corn production, yield and area harvested in million bushels (million tonnes), bushel/acre (tonne/hectare) and acres (hectares), respectively.

Year	Production	Yield	Area Harvested
1995	7,374 (187)	114 (7.2)	65.2 (26.4)
1996	9,233 (234)	127 (8.0)	72.6 (29.4)
1997	9,207 (234)	127 (8.0)	72.7 (29.4)
1998	9,759 (248)	134 (8.4)	72.6 (29.4)
1999	9,431 (240)	134 (8.4)	70.6 (28.6)
2000	9,970 (253)	137 (8.6)	72.7 (29.4)

Table 5. Historical US corn production in million bushels (million tonnes) for the five most productive states.

Year	Iowa	Illinois	Nebraska	Minnesota	Indiana
1995	1,402 (35.6)	1,130 (28.7)	855 (21.7)	732 (18.6)	599 (15.2)
1996	1,718 (43.6)	1,469 (37.3)	1,187 (30.1)	869 (22.1)	670 (17.0)
1997	1,642 (41.7)	1,425 (36.2)	1,135 (28.8)	851 (21.6)	702 (17.8)
1998	1,769 (44.9)	1,473 (37.4)	1,240 (31.5)	1,033 (26.2)	760 (19.3)
1999	1,758 (44.6)	1,491 (37.9)	1,154 (29.3)	990 (25.1)	748 (19.0)
2000	1,752 (44.5)	1,691 (42.9)	1,006 (25.5)	977 (24.8)	816 (20.7)

Table 6. US 1999 corn yields in the five states with the largest production and the five states with the highest yields (NASS 2001).

State	Yield		Production	
	(bushels/ acre)	(tonne/ hectare)	(million bushels)	(million tonnes)
Iowa	149	9.4	1,758	44.6
Illinois	140	8.8	1,491	37.9
Nebraska	139	8.7	1,154	29.3
Minnesota	150	9.4	990	25.1
Indiana	132	8.3	748	19.0
Arizona	195	12.3	5.8	0.1
New Mexico	180	11.3	14.9	0.4
Washington	180	11.3	18	0.5
Oregon	175	11.0	5.2	0.1
California	165	10.4	33.8	0.9

Table 7. US corn consumption 1980 to 2000 (million bushels).

Year	Fuel Ethanol	Beverage Alcohol	HFCS	Glucose	Starch
1980	35	78	165	156	151
1981	86	86	183	160	146
1982	140	110	214	165	150
1983	160	88	265	167	161
1984	232	84	310	167	172
1985	271	83	327	169	190
1986	290	85	338	171	214
1987	279	77	358	173	226
1988	287	107	361	182	215
1989	321	109	368	193	219
1990	349	80	379	200	219
1991	398	81	392	210	225
1992	426	83	415	214	218
1993	458	83	441	223	225
1994	533	100	459	231	230
1995	396	125	473	237	226
1996	429	130	492	246	238
1997	481	133	513	245	246
1998	526	127	530	234	240
1999	555	131	565	240	250
2000	615	130	550	220	255

Table 8. Summary of corn processes and coproducts.

Process	Brief Description	Primary product	Coproducts
Dry Grind Ethanol	Corn is ground, cooked, liquefied, saccharified; fermented and distilled for manufacture of ethanol.	Ethanol (beverage, industrial, fuel)	DDGS*, carbon dioxide
Modified Dry Grind Ethanol	Corn is soaked, lightly ground, germ and fiber removed, finely ground, cooked, liquefied, saccharified; fermented and distilled for manufacture of ethanol.	Ethanol (beverage, industrial, fuel)	DDGS-modified, germ (corn oil), fiber (nutraceuticals), carbon dioxide
Corn Wet Milling	Corn is steeped, lightly ground, germ removed, finely ground, fiber removed, protein separated from starch, starch further processed. Results in a 99.5% pure starch product.	Starch, Ethanol, High fructose corn syrup	corn oil, corn gluten feed, corn gluten meal, carbon dioxide
Dry Milling	Small amount of water added to corn, kernel is abraded to separate components of pericarp, germ and endosperm. Remaining process is primarily physical size separation.	Flaking grits	brewers grits, small grits, corn meal and cones, corn flour

* distillers dried grains with solubles

Table 9. Coproduct yields from ethanol processes (wet milling, dry grind ethanol, modified dry grind ethanol). Basis: one bushel corn.

Process	**Coproducts**
Dry grind ethanol	2.6 gallons of ethanol and 15 pounds of DDGS*
Modified dry grind ethanol	2.5 gallons of ethanol and 3.4 pounds of germ and 3.8 pounds of fiber and 7.8 pounds of modified DDGS
Wet milling	2.5 gallons of ethanol or 31.5 pounds of starch or 33.0 pounds of sweetener and 1.5 pounds of corn oil and 3.0 pounds of corn gluten meal and 12.4 pounds of corn gluten feed

* distillers dried grains with solubles

Table 10. Historical price data for corn processing coproducts* in US$ per ton (Anonymous 2000).

Year	**DDGS**	**CGF**	**CGM**	**Crude Corn Oil**
1991	122.34	101.49	265.79	567.80
1992	122.84	95.95	284.60	479.80
1993	123.79	88.62	286.61	435.40
1994	106.70	82.77	221.95	546.80
1995	151.37	116.47	319.35	531.60
1996	142.87	93.05	341.50	490.40
1997	107.78	69.65	290.45	499.00
1998	85.77	59.87	234.76	597.40
1999				467.20
2000				299.20
Avg	120.43	88.48	280.63	491.46
Std. Dev.	20.81	17.87	39.86	83.41

*Abbreviations are DDGS: distillers dried grains with solubles; CGF: corn gluten feed; CGM: corn gluten meal

Table 11. Estimates of average historical coproduct values from the conventional and modified dry grind ethanol processes.

	Coproduct values (US estimates, $/lb)	
Coproduct	**Modified dry grind ethanol**	**Conventional dry grind ethanol**
Ethanol	1.25 ($/gal)	1.25 ($/gal)
Crude corn oil	0.246*	None
Fiber oil	3.50 to 4.50**	None
Modified DDGS	0.06 to 0.10	0.060*

*Ten year historical average (1991-2000) from USDA-ERS data.
**Based on competitive products.

Table 12. Various uses for corn oil.

Cooking oil	Chemicals and insecticides
Margarine	Lecithin (for pharmaceuticals, cosmetics, inks)
Mayonnaise	Paint and varnish
Potato chips	Rubber substitutes
Salad dressing	Rust prevention (surface coatings)
Sauces, seasoning	Soap
Shortening	Soluble oil (leather and tanning)
Soups	Textiles
Carriers (vitamins, medicines)	Boiler fuel when energy cost is high

Table 13. Summary of raw material inputs, processing plant and product outputs for a modified dry grind ethanol facility.

Raw Materials	**Processing Plant**	**Products (annual production)**
Crop Land: 108,000 ac	US$49 million	Ethanol: 31 mmgy
Corn: 12.5 million bu/year	Grind: 35,700 bu/day	Total coproducts: 93,900 ton
Water: 300,000 gal/day		Modified DDGS: 48,800 ton
		Germ: 21,300 ton
		Fiber: 23,800 ton

Table 14. Revenue generated by a 33,400 bu/day conventional dry grind ethanol facility.

Capital Investment						
Purchased equipment					$	10,780,142
Purchased equipment installation						2,425,532
Instrumentation (installed)						1,347,518
Piping (installed)						1,886,525
Electrical (installed)						2,156,028
Buildings (including service connections)						3,234,043
Yard improvement						539,007
Service facilities						2,695,035
Land						539,007
Engineering and supervision						4,042,553
Construction expense						2,695,035
Contractor's fee						1,617,021
Contingency						4,042,553
Buildings (20 year life) and Equipment (12 year life)					$	38,000,000
Income						
Ethanol	30.4	million gal / yr	$ 1.25	per gal		38,000,000
DDGS	175	million lb / yr	0.060	per lb		10,561,004
				Total Income	$	48,561,004
Expenses						
Corn	11.7	million bu / yr	$ 2.30	per bu		26,892,308
Chemicals, Enzymes, Denaturants						3,450,000
Power						3,108,000
Salaries (30 employees; including benefits, taxes, insurance)						1,150,000
Direct and Indirect (maintenance, repairs, water, handling)						1,100,000
Depreciation and Amortization						2,425,000
General and Administrative (including marketing)						900,000
				Total Expenses	$	39,025,308
				Net Income	$	9,535,696
				Pay Back Period (years)		4.0

Table 15. Estimated capital investment and revenue generated by a 35,700 bu/day modified dry grind ethanol facility based on historical values for germ (1991-2000).

Capital Investment					
Germ and fiber recovery equipment (installed)*					$ 11,000,000
Other purchased equipment					10,780,142
Purchased equipment installation					2,425,532
Instrumentation (installed)					1,347,518
Piping (installed)					1,886,525
Electrical (installed)					2,156,028
Buildings (including service connections)					3,234,043
Yard improvement					539,007
Service facilities					2,695,035
Land					539,007
Engineering and supervision					4,042,553
Construction expense					2,695,035
Contractor's fee					1,617,021
Contingency					4,042,553
				Buildings (20 year life) and Equipment (12 year life)	$ 49,000,000
Income					
Ethanol	31.3	million gal / yr	$ 1.25	per gal	39,121,875
Germ	42.6	million lb / yr	$ 0.098	per lb	4,183,675
Fiber	47.6	million lb / yr	$ 0.018	per lb	856,300
Modified DDGS	97.6	million lb / yr	$ 0.096	per lb	9,374,227
				Total Income	$ 53,536,076
Expenses					
Corn	12.5	million bu / yr	$ 2.30	per bu	28,793,700
Chemicals, Enzymes, Denaturants**					3,691,500
Power	(20% increase from conventional dry grind)				3,729,600
Salaries	30 employees (including benefits, taxes, insurance)				1,150,000
Direct and Indirect (maintenance, repairs, water, handling)**					1,177,000
Depreciation and Amortization **					2,594,750
General and Administrative (including marketing)**					963,000
				Total Expenses	$ 42,099,550
				Net Income	$ 11,436,526
				Pay Back Period (years)	4.3

*Germ and fiber recovery capital includes all expenses needed to install equipment in a new facility or retrofit to existing dry grind ethanol facility. Costs for this item includes instrumentation, piping, electrical, buildings, and associated expenses.

** Proportional increase assumed from increasing production 7% from 11.7 to 12.5 million bu/yr.

Table 16. Estimated capital investment and revenue generated by 35,700 bu/day modified dry grind ethanol facility based on 2001 prices for germ (Jan-May 2001).

Capital Investment						
Germ and fiber recovery equipment (installed)*						$ 11,000,000
Other purchased equipment						10,780,142
Purchased equipment installation						2,425,532
Instrumentation (installed)						1,347,518
Piping (installed)						1,886,525
Electrical (installed)						2,156,028
Buildings (including service connections)						3,234,043
Yard improvement						539,007
Service facilities						2,695,035
Land						539,007
Engineering and supervision						4,042,553
Construction expense						2,695,035
Contractor's fee						1,617,021
Contingency						4,042,553
					Buildings (20 year life) and Equipment (12 year life)	$ 49,000,000
Income						
Ethanol	31.3	million gal / yr	$	1.25	per gal	39,121,875
Germ	42.6	million lb / yr	$	0.049	per lb	2,104,394
Fiber	47.6	million lb / yr	$	0.018	per lb	856,300
Modified DDGS	97.6	million lb / yr	$	0.096	per lb	9,374,227
					Total Income	$ 51,456,796
Expenses						
Corn	12.5	million bu / yr	$	2.30	per bu	28,793,700
Chemicals, Enzymes, Denaturants**						3,691,500
Power	(20% increase from conventional dry grind)					3,729,600
Salaries	30 employees (including benefits, taxes, insurance)					1,150,000
Direct and Indirect (maintenance, repairs, water, handling)**						1,177,000
Depreciation and Amortization**						2,594,750
General and Administrative (including marketing)**						963,000
					Total Expenses	$ 42,099,550
					Net Income	$ 9,357,246
					Pay Back Period (years)	5.2

*Germ and fiber recovery capital includes all expenses needed to install equipment in a new facility or retrofit to existing dry grind ethanol facility. Costs for this item includes instrumentation, piping, electrical, buildings, and associated expenses.

** Proportional increase assumed from increasing production 7% from 11.7 to 12.5 million bu/yr.

7. Figures

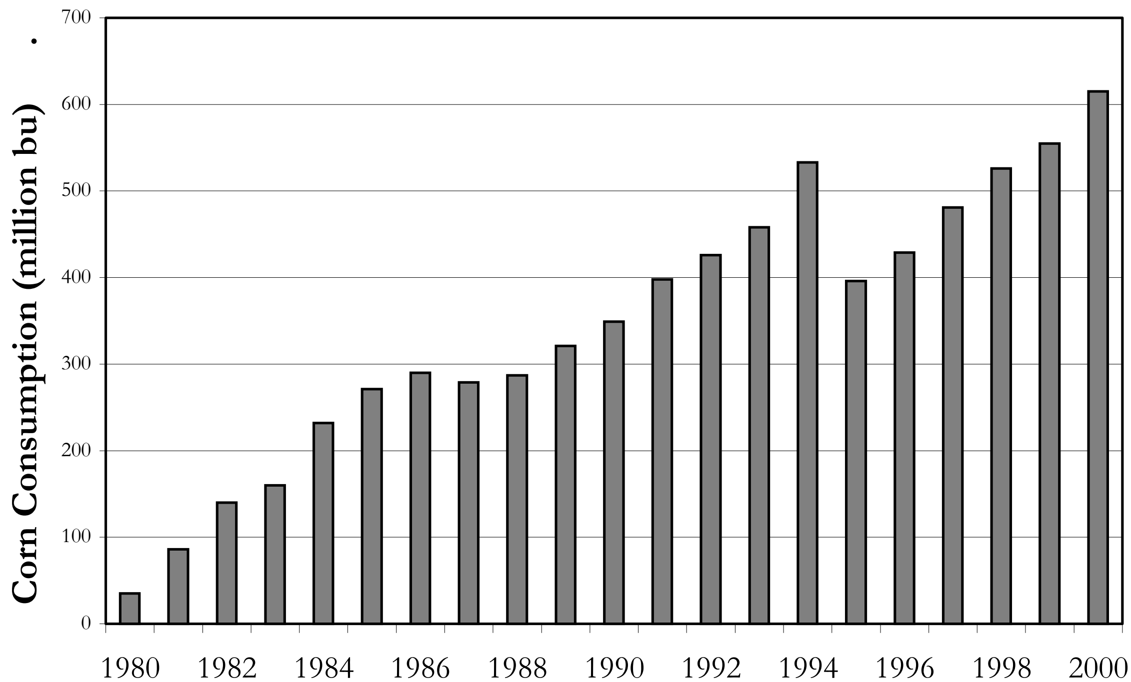

Figure 1. Use of corn from US for production of fuel ethanol.

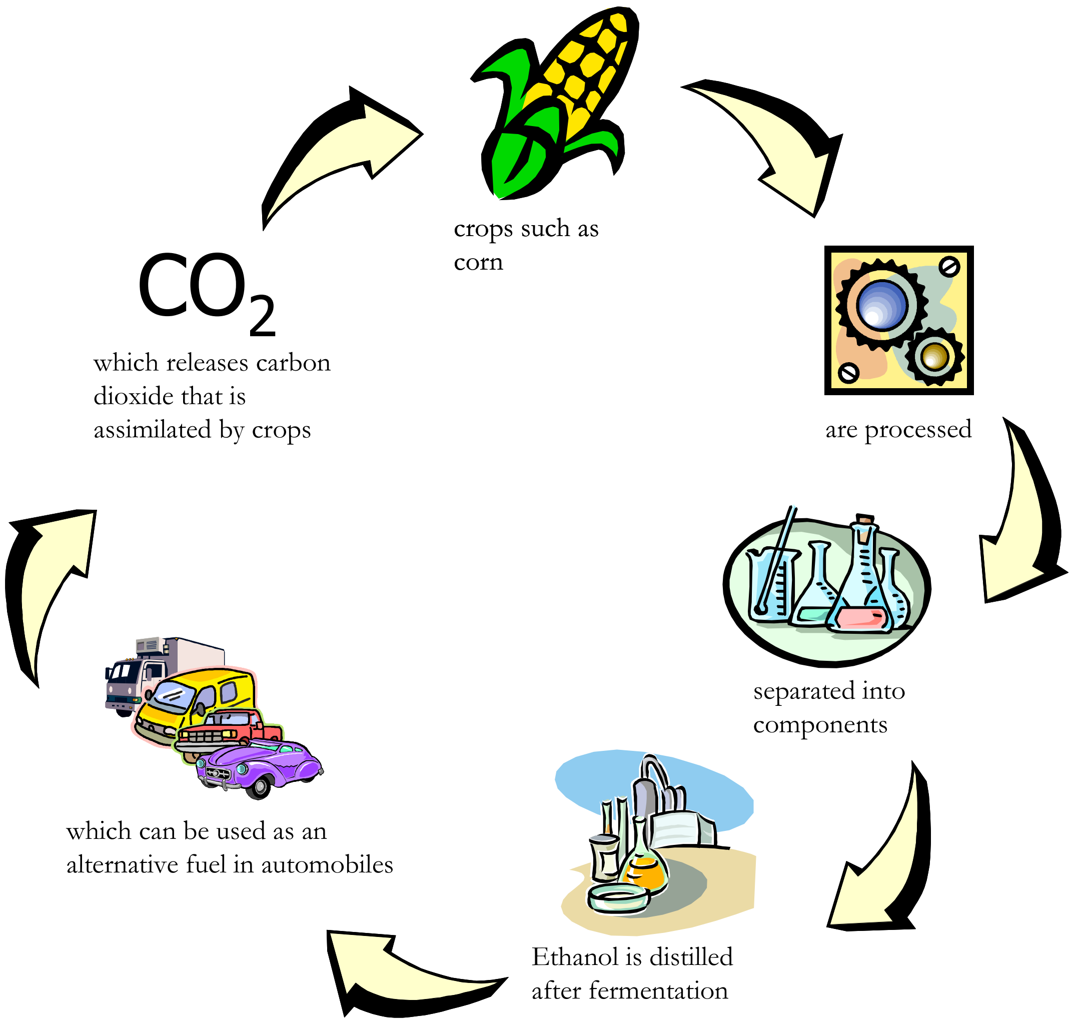

Figure 2. The carbon cycle (adapted from: Renewable Fuels Association 2000).

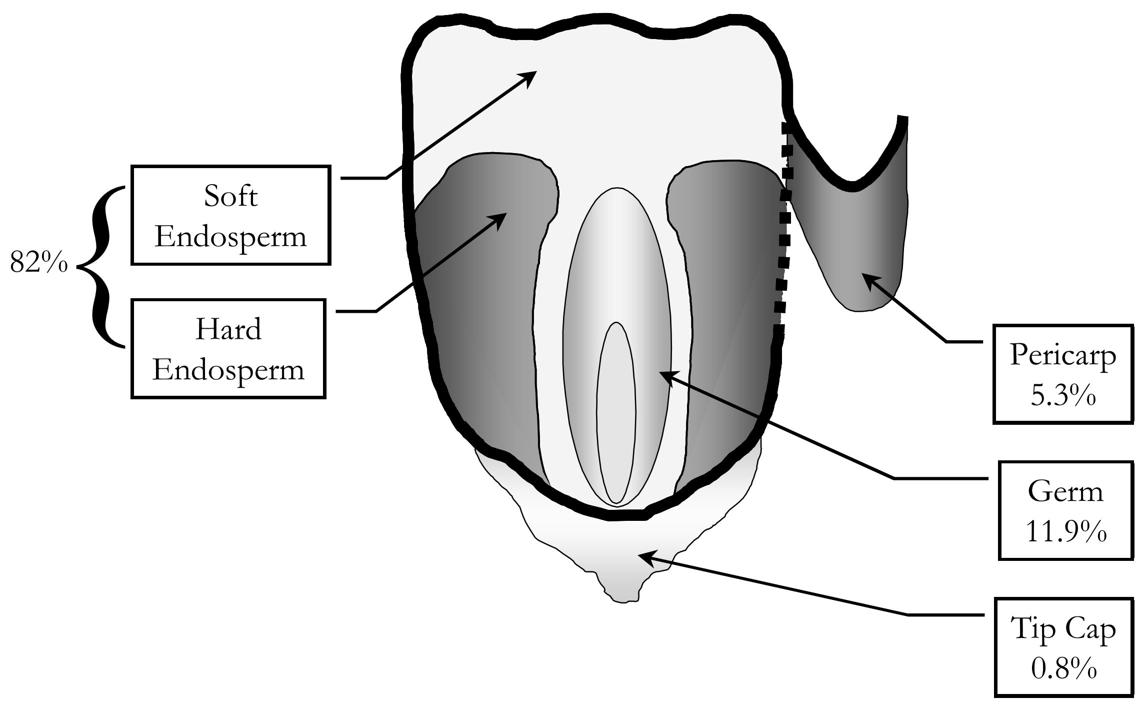

Figure 3. The corn kernel: a fundamental basis for all corn processes.

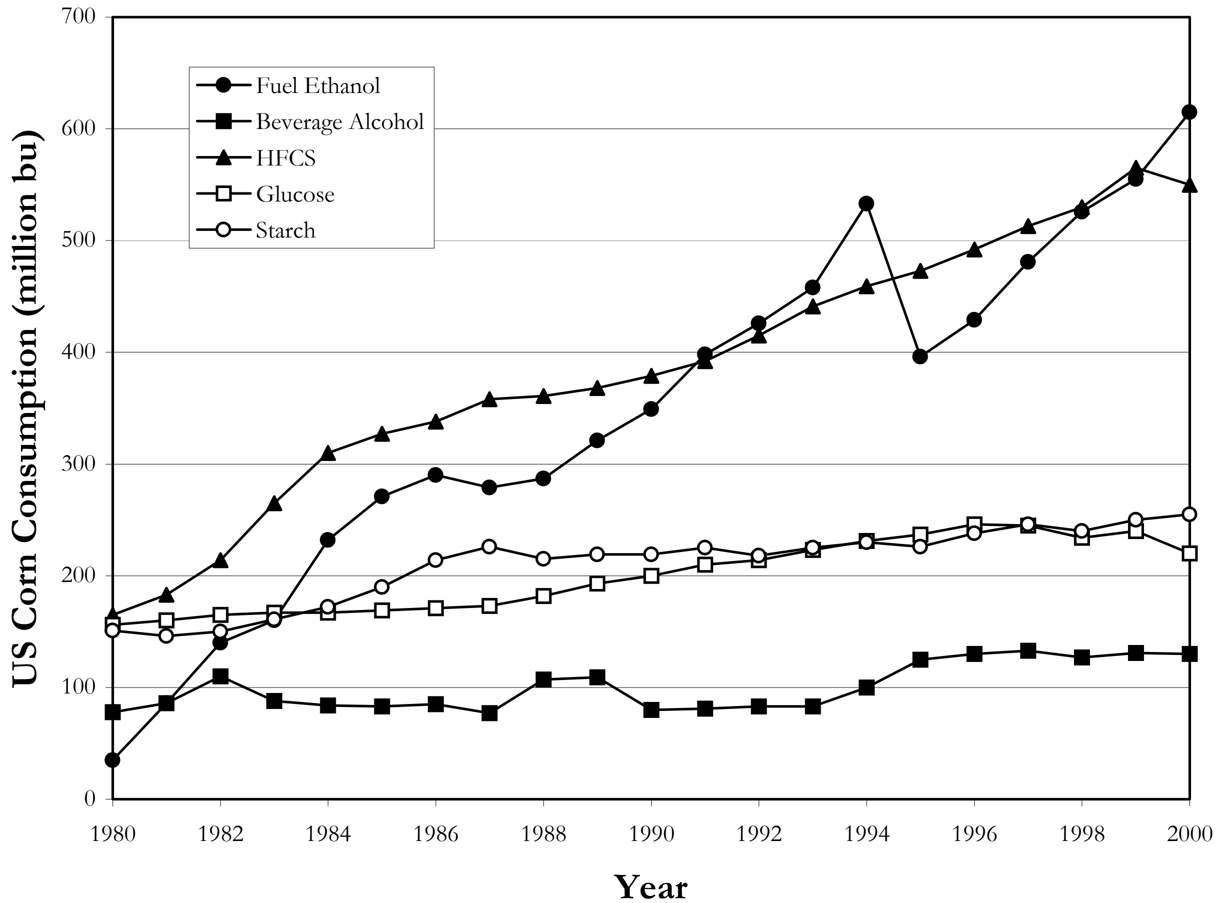

Figure 4. US corn consumption (million bushels).

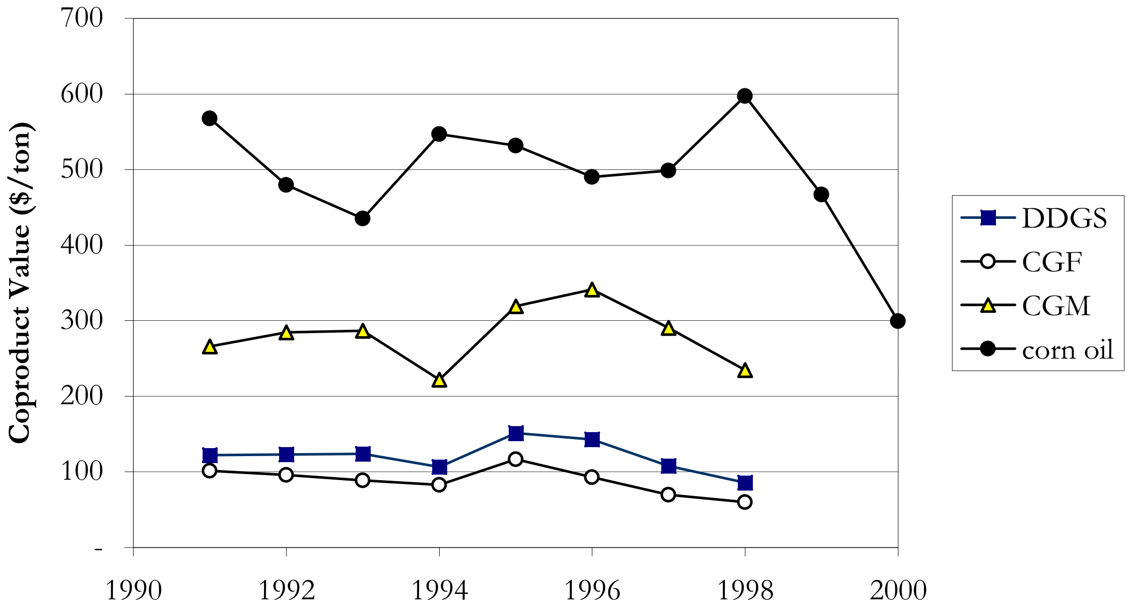

Figure 5. Historical price of coproducts from corn processing (Anonymous 2000).

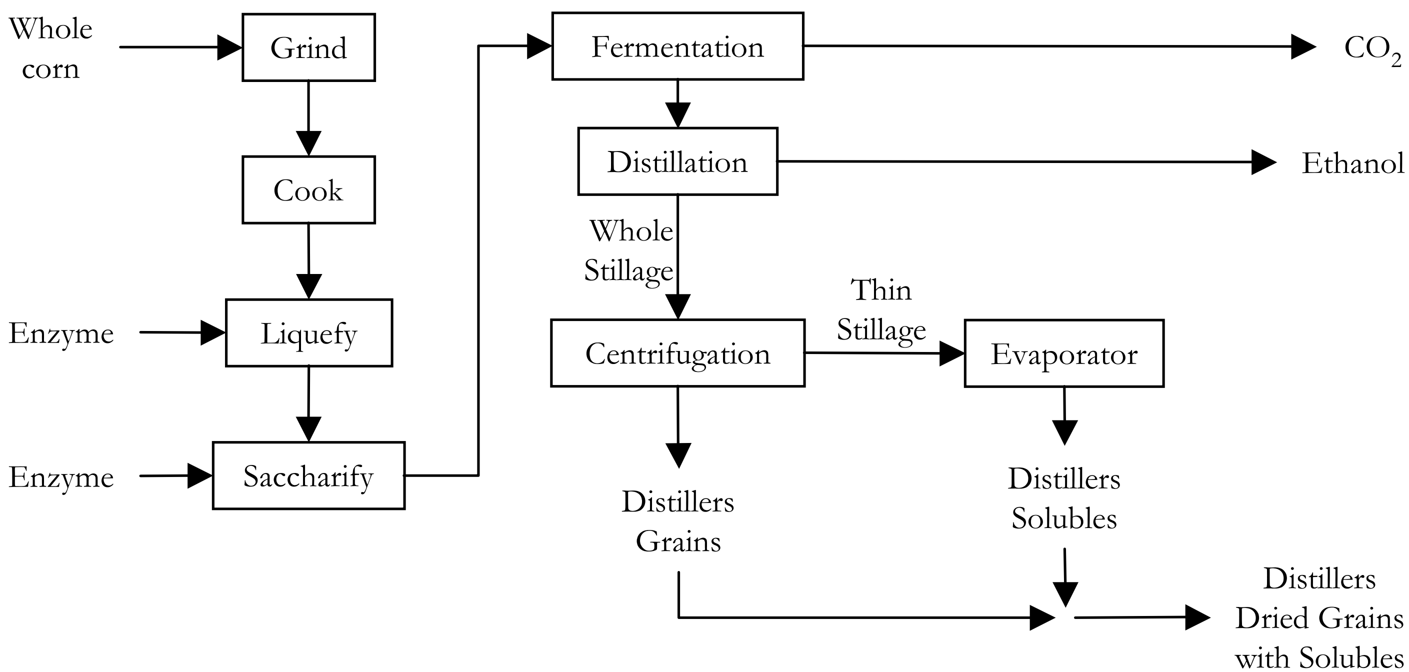

Figure 6. A schematic of the conventional dry grind ethanol process.

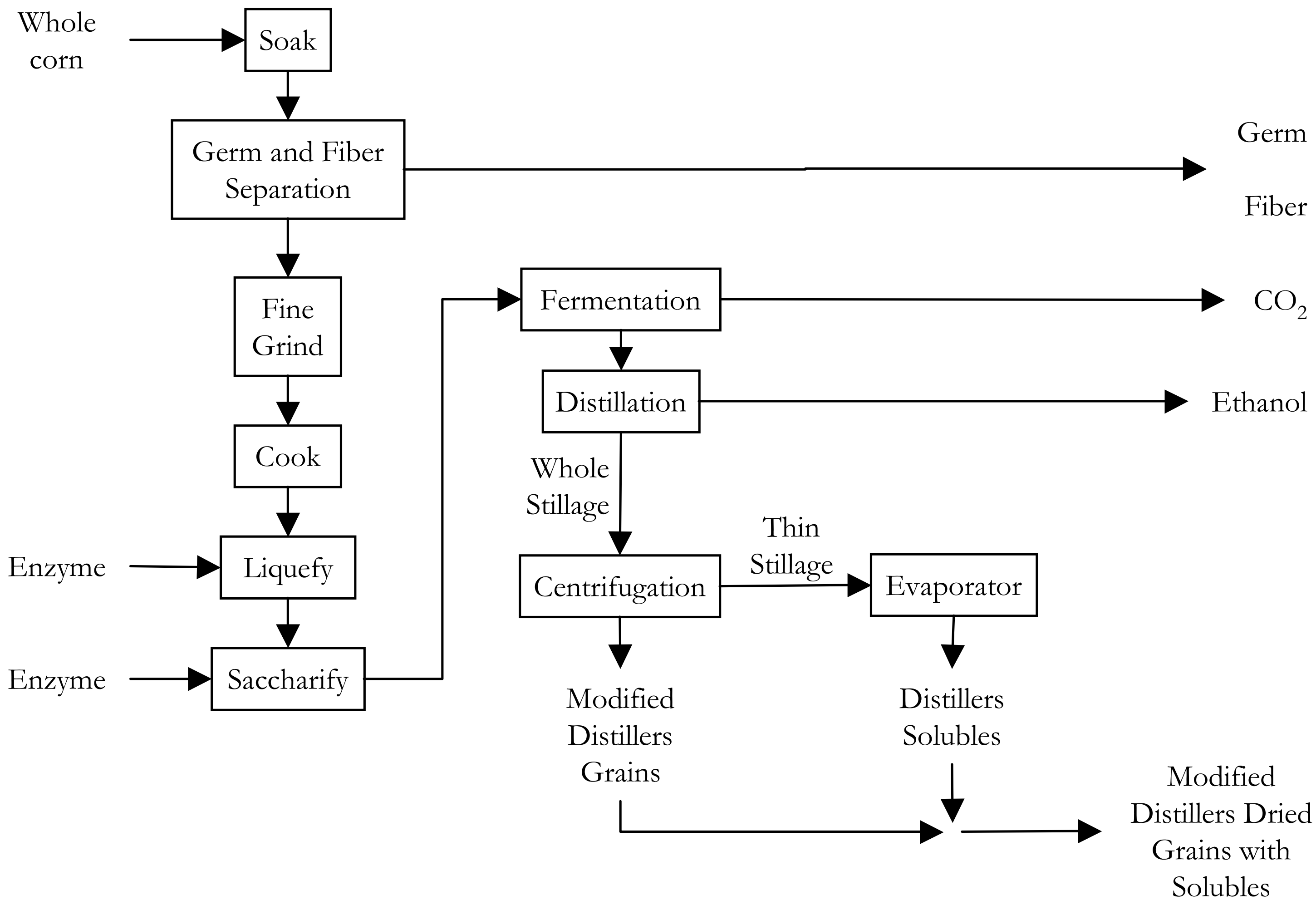

Figure 7. A schematic of the modified dry grind ethanol process with germ and fiber recovery.

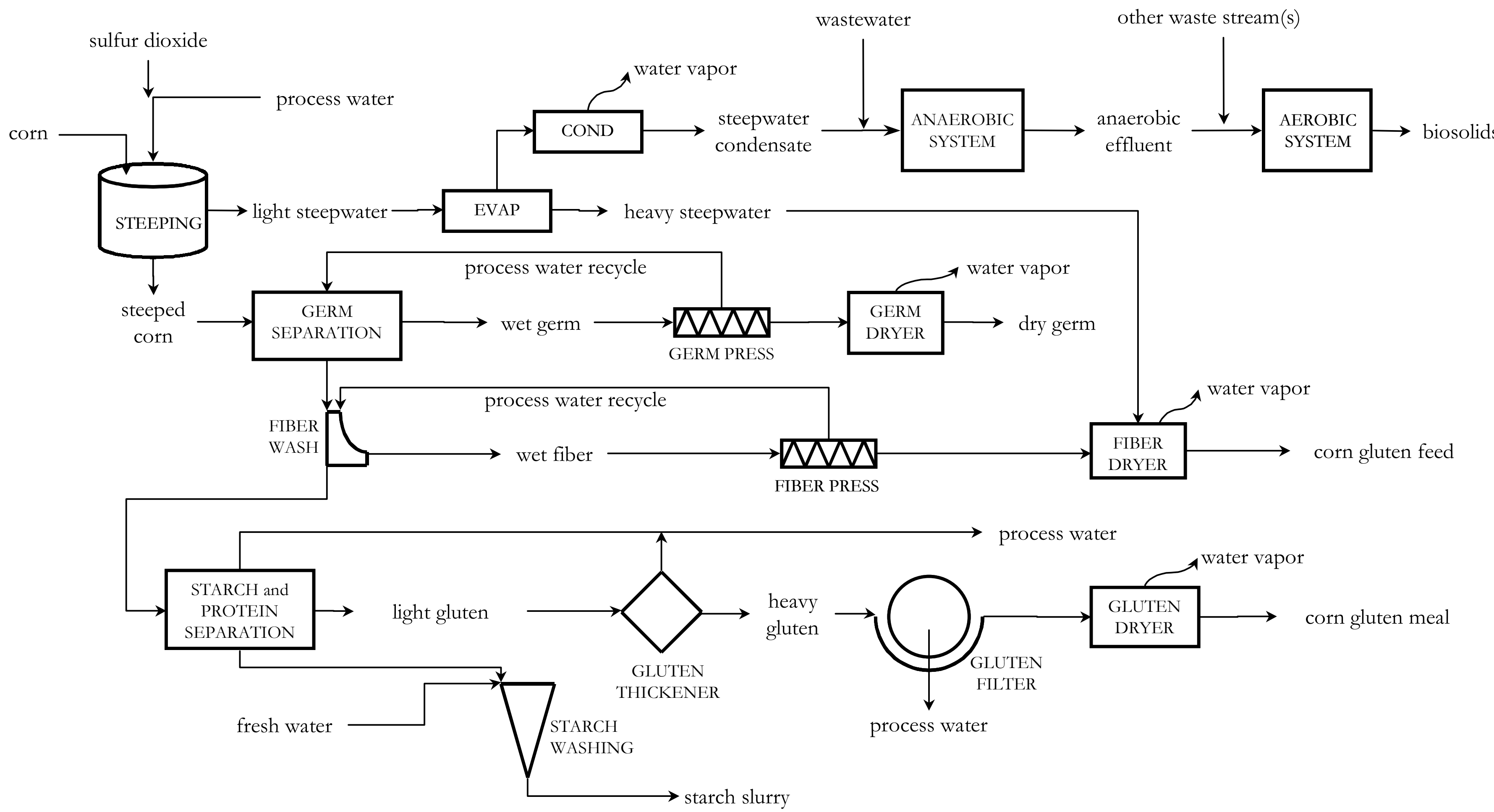

Figure 8. A schematic of the corn wet milling process.