

CHAPTER 4

Biofuel Feedstocks

There are many forms of feedstocks for biofuel production. Animal manures and municipal solid wastes have been used to generate methane for on-farm and municipality energy uses. Fuel ethanol has been produced commercially using plant-derived starch and sugar feedstocks. Technologies for production of ethanol from lignocellulosic biomass and biodiesel from seed and algal oils have been developed and tested at various scales up to semicommercial demonstration plants. This chapter discusses the characteristics of feedstocks relevant to biofuel production and their availability in the United States and other regions of the world where data is available. Conversion technologies of these feedstocks for biofuel production will be discussed in the following chapters.

4.1 Starch Feedstocks

4.1.1 Cereal Grains

Cereal grains are used mostly for food and feed. However, because of their high starch contents they are also good feedstocks for conversion to biofuels and other bio-based products. Ethanol is the only biofuel that has been produced commercially from these feedstocks in large quantities. Starch contents and theoretical ethanol yield of cereal grains which are relevant to ethanol production are summarized in Table 4.1.

Starch is a polymer of glucose and consists of two main structural components, amylose and amylopectin. *Amylose* is essentially a linear polymer in which the glucose residues are connected by the α -1,4 linkages (Fig. 4.1). The other main component of starch is *amylopectin*, which is a larger and branched molecule with both α -1,4 and α -1,6 linkages (Fig. 4.2). Most common starch contains about 25 percent amylose and 75 percent amylopectin. Starch in waxy grain varieties contains amylopectin almost exclusively (greater than 98 percent). Starch can be hydrolyzed by enzymes to produce the monomeric sugar glucose, which is readily metabolized by the yeast *Saccharomyces cerevisiae* to produce ethanol at high yields. Starch processing is a mature industry, and commercial enzymes required for starch

Feed grain	Starch (%)	Theoretical ethanol yield*	
		(L/kg)	(gal/MT†)
Corn	72 (65–76)	0.52	125
Wheat	77 (66–82)	0.55	132
Barley	57 (55–74)	0.41	98
Sorghum	72 (68–80)	0.52	125
Oat	58 (45–69)	0.42	101
Rice	79 (74–85)	0.57	137

*Theoretical yield of ethanol is 0.51 kg ethanol/kg glucose. Upon hydrolysis, 1 kg starch produces 1.11 kg glucose.

†MT: metric ton.

Source: Adapted from Dairy Research and Technology Centre (http://www.afns.ualberta.ca/Hosted/DRTC/Articles/Barley_Dairy.asp) and Juliano, 1993.

TABLE 4.1 Starch and Theoretical Ethanol Yield of Relevant Cereal Grains (Dry Basis)

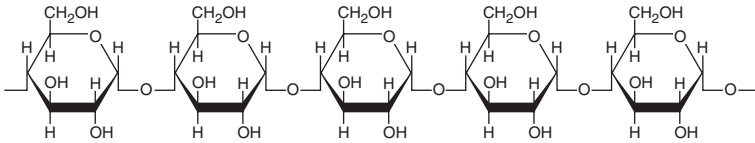


FIGURE 4.1 Amylose.

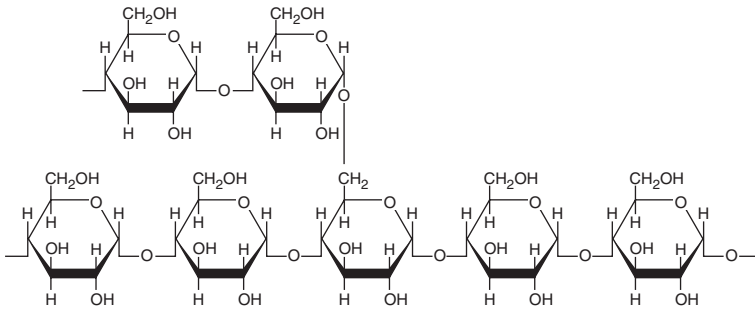


FIGURE 4.2 Amylopectin.

hydrolysis are available at low costs. Hydrolysis of starch in commercial practice will be discussed in the next chapter where ethanol production from grain feedstocks is considered.

In addition to starch cereal grains also contain other components, which can be recovered into value-added coproducts in the ethanol fermentation process.³ Sales of these high-value coproducts play an

important role in determining the process economics of fuel ethanol production.

4.1.1.1 Corn

Corn is the main feedstock for ethanol production in the United States and Canada. More than 95 percent of the ethanol currently produced in the United States comes from corn. In Canada, this figure is about 85 percent.⁴ The United States is the largest producer of corn in the world. In 2005, 280 million MT of corn was produced in the United States. China is the second largest corn producer. In 2005, China produced 131 million MT of corn.⁵ One-fifth of this amount was used for industrial applications and ethanol production accounted for 40 percent of total industrial corn use. The corn demand for ethanol production in China increased so fast that in December 2006 the government ordered suspension of all new development of the corn-based ethanol industry to avert further increase in corn price, which jumped 5 percent in the previous month.⁶

The total corn production and the corn usage for ethanol production in the United States from 1992 to 2007 are shown in Fig. 4.3. The corn farm price for the same period is shown in Fig. 4.4. Figure 4.5 compares the percentages of corn usage for ethanol production with respect to

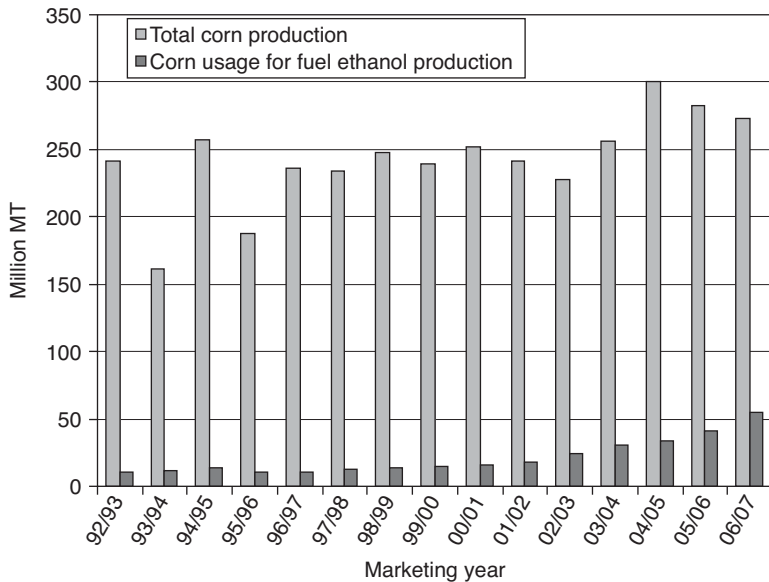


FIGURE 4.3 Total corn production and corn usage for ethanol production in the United States. (Adapted from USDA Feed Outlook, 2007.)

Note: Marketing year for corn begins in September and ends in August the following year. Data in bushel is converted to metric ton assuming 56 lb/bu. The latest data is projected.

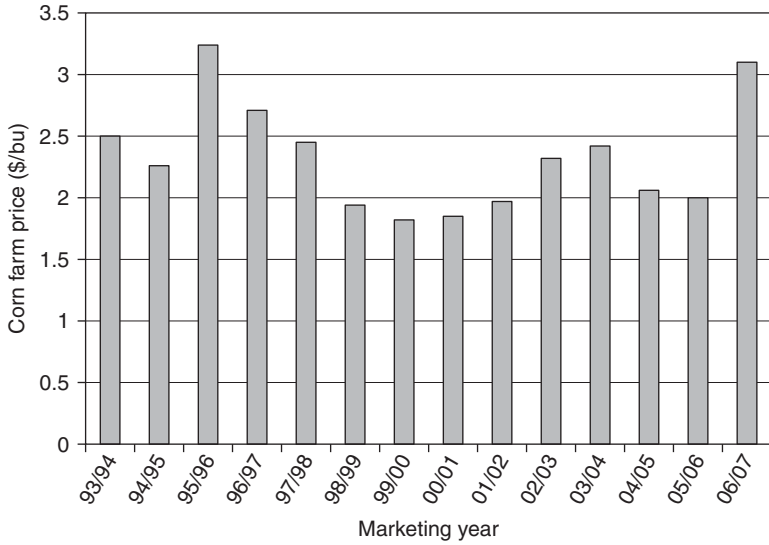


FIGURE 4.4 Corn farm price in the United States from 1993 to 2007. (Adapted from *USDA Feed Outlook, 2007.*)

Note: The latest data is projected.

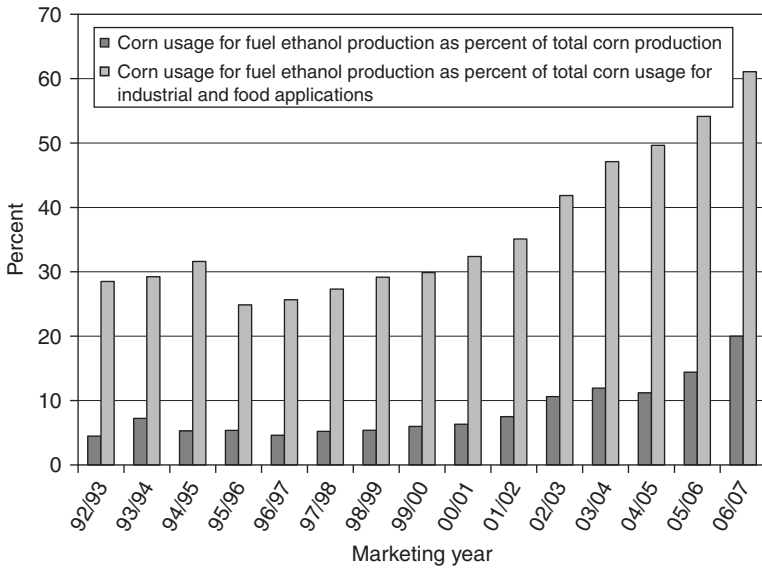


FIGURE 4.5 Corn usage for ethanol production as percent of total corn production and total corn usage for industrial applications in the United States. (Adapted from *USDA Feed Outlook, 2007.*)

Note: The latest data is projected.

total corn production and total corn usage for all industrial and food applications (fuel ethanol, high fructose corn syrup (HFCS), starch, glucose and dextrose, alcoholic beverages, cereals, and other minor applications). The data clearly shows an increasing trend in corn usage for ethanol production, especially after the marketing year of 2000–2001. This increase did not seem to have an impact on total corn production and corn farm price. However, the corn farm price jumped to \$3.12/bu in November 2006, which was 76 percent higher than that of the same period of the previous year (\$1.77/bu). The U.S. Department of Agriculture (USDA) also predicted an increase in corn farm price for the marketing year of 2006–2007.⁷ Corn production in the United States is concentrated in the “corn belt” in the Midwest. Illinois, Indiana, Iowa, Minnesota, and Nebraska are the states with largest corn production. In 2005 corn production in these five states accounted for 65 percent of the total U.S. production. Corn production by individual states in the United States is given in App. 4.1. The USDA predicted that corn production in the United States would be increased to meet future demand and could reach 400 million MT. About 25 percent of this could be used for ethanol production, which would produce 42 billion liters (11 billion gallons) fuel ethanol.⁷

In addition to starch the corn kernel also contains 10 percent protein, 4.5 percent oil, and 10 to 15 percent other materials such as fiber and ash. Protein, oil, and fiber can be recovered in the ethanol fermentation process and sold as coproducts. The rule of thumb used in the U.S. ethanol industry is that for 1 bu of corn (56 lb at 15.5 percent moisture), one can make 2.5 to 2.8 gal ethanol plus 17 lb distillers dried grains without or with solubles (DDG/S) in the dry-grind process or 1.6 lb corn oil, 2.6 lb gluten meal (60 percent protein), and 13.5 lb gluten feed (20 percent protein) in the wet-mill process.⁸ DDGS is the key coproduct in the dry-grind ethanol process. Revenues brought in by selling this coproduct for animal feed help make the process economically viable. Corn oil, corn gluten meal, and corn gluten feed also are important coproducts in the wet-mill process.

4.1.1.2 Wheat

Wheat starch is currently used for ethanol production at only two plants in the United States. In other places, however, it is an important feedstock for production of this biofuel. In Canada, 15 percent of the ethanol produced by fermentation comes from wheat.⁴ In Europe and Australia, wheat is the primary feedstock considered for expansion of the starch-based ethanol industry. The trend of wheat production in Canada and Australia from 1990 to 2004 is shown in Fig. 4.6. In the European Union (EU), the production of wheat in 2004 was totaled at 124 million MT.⁵

Currently production of ethanol from wheat in Canada is practiced on a relatively modest scale in the western part of the country. However, there have been proposals to significantly expand

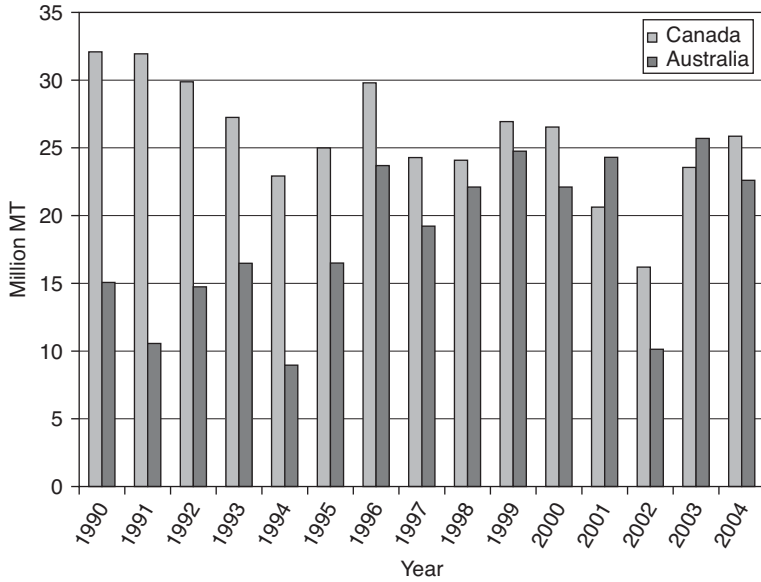


FIGURE 4.6 Total wheat production in Canada and Australia from 1990 to 2004. (Adapted from United Nations FAOSTAT, 2004.)

ethanol production from wheat in Saskatchewan and Manitoba. Plans also are devised for construction of several wheat-based ethanol plants in Australia and the European Union. Wheat normally has higher protein contents than corn. Canadian wheat varieties and their protein contents are shown in Table 4.2. Wheat protein has better quality for food and feed applications than corn protein because it

Wheat class	Typical protein level (% - dry basis)
Canadian Western Red Spring	13.2
Canadian Western Extra Strong	12.2
Canadian Prairie Spring Red	11.5
Canadian Western Red Winter	11.3
Canadian Prairie Spring White	11.2
Canadian Western Soft White	10.5
Canadian Western Amber Durum	12.8

Source: Adapted from (S&T)² Consultants Inc., 2003.

TABLE 4.2 Canadian Wheat Varieties and Their Protein Contents

contains the essential amino acid lysine. However, since wheat protein is insoluble in water it may cause problems in ethanol production, especially in downstream processing. Thus, only those with low protein contents such as Canadian Prairie Spring (Red and White), Canadian Western Red Winter, and Canadian Western Soft White are suitable for ethanol production. The use of low-protein wheat for ethanol production has the additional advantage of increased starch content. Coproducts of ethanol production include DDGS and gluten, which constitutes 80 to 90 percent of the wheat protein. Gluten is an important additive in bakery and breakfast foods and in processed meat and fish products. It is widely used in vegetarian cuisine, especially in East and Southeast Asia, where there are large Buddhist populations. Wheat also contains oil but the levels are low (less than 3 percent).

4.1.1.3 Barley

Barley is a potential alternative grain feedstock for ethanol production in the United States, especially in the Mid-Atlantic and some Midwest states, where it can be grown as a winter crop. It thus offers potential for double cropping with soybean. Barley production in the United States has declined steadily in the last 15 years, from 9.2 million MT in 1990 to 4.6 million MT in 2005.⁷ However, this trend may be reversed if barley becomes a feedstock for ethanol production. If barley production is brought back to the 1990 level and all of the added barley is used for ethanol production, a theoretical ethanol yield of 1.7 billion liters (450 million gallons) can be realized. The Southeastern states potentially can produce 14.5 million MT (32 billion lb) of barley to be used solely for ethanol production.¹⁰ This will add 5.4 billion liters (1.4 billion gallons) more ethanol. Despite its potential for being a strong feedstock candidate, production of ethanol from barley faces several problems. Barley has much lower starch content than corn (Table 4.1), thus ethanol yield per unit mass will be significantly lower. Barley hull is abrasive and can cause damage to milling and grain handling equipment. Lastly, barley contains significant levels of β -glucan, a linear unbranched polysaccharide of β -D-glucose like cellulose, but with one β -1,3 linkage for every three or four β -1,4 linkages (Fig. 4.7).

Beta-glucan is soluble in hot water. The soluble β -glucan causes the viscosity of the fermentation mash to rise to such levels that at 30 percent total dry solids, which is the typical condition used in industrial ethanol fermentation, it is practically impossible to provide adequate mixing to the mash. The presence of β -glucan in the coproduct DDGS makes it a poor feed for monogastric animals such as poultry and swine. Considerable research efforts have been made to alleviate the problems associated with using barley for ethanol production. Researchers at the Virginia Polytechnic Institute and State University have developed hulled barley varieties with higher

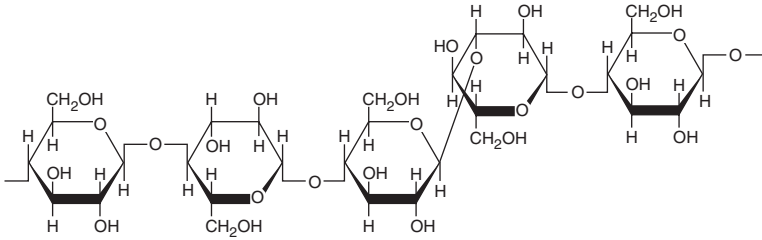


FIGURE 4.7 β -Glucan.

starch contents and hull-less barley varieties with lower fiber, no abrasiveness, and higher starch contents (approaching those of corn). Enzyme companies such as Novozymes and Danisco have developed commercial products to reduce the viscosity of the mash. These product lines include Viscozymes (Novozymes) and Optimash (Danisco). The Eastern Regional Research Center (ERRC) of the USDA's Agricultural Research Service (ARS) currently has a program with industrial collaboration to develop fermentation processes for ethanol production using both hulled and hull-less barley as feedstocks. Since the cost of ethanol production from barley in a conventional process is higher than that from corn due to lower ethanol yield, development of value-added coproducts or purchase of barley at a suitable cost relative to corn will be essential in a barley-based process. Barley protein contains lysine and hence is a valuable coproduct. Beta-glucan may be a second potential high-value coproduct due to its many health benefits that have recently been reported such as speeding of the immune response and reduction of the LDL cholesterol levels.

4.1.1.4 Sorghum

Sorghum is another alternative grain feedstock for ethanol production. It has starch content similar to that of corn (Table 4.1). In 2006, 7.3 million MT of sorghum grains were produced in the United States. About 15 percent of this was used for ethanol production at eight plants in Kansas and Nebraska. Five more sorghum-based ethanol plants were proposed in these two states.¹¹ The total world production for 2006 was 41.2 million MT. Nigeria and India were ranked second and third behind the United States in sorghum production.⁵ Sorghum and corn are interchangeable in a dry-grind ethanol plant. Several ethanol plants in the United States use both feedstocks. Ethanol yields from sorghum and from corn are equal. The composition of the DDGS coproducts in ethanol production from corn and sorghum also are very similar. In a proposed process using decortication (removal of the bran and outer layers of the grain) high-value coproducts such as phytochemicals can be recovered from the bran, and higher loadings of starch in the fermenter can be made possible.¹² One advantage of

sorghum is that it is very drought resistant and heat tolerant, probably because of a waxy coating on its leaves and stems that keeps water in the plant for periods of intense heat. Thus, it is a suitable feedstock for ethanol production in arid regions such as Africa and South Asia.

4.1.1.5 Oat

Oat is a potential feedstock for ethanol production with total world production of 24 million MT in 2005.⁵ It has not been used commercially for ethanol production because of a number of reasons. It has relatively low starch content (Table 4.1) and hull mass as high as 34 percent of the grain weight, which lowers starch loading in the fermenter. The grain also contains β -glucan and pentosans, which upon solubilization in hot water, cause significant rise in the mash viscosity. Commercial production of ethanol from oat grains can be made possible by making process modifications, which include removal of the hulls along with other suspended particles by decantation or filtration prior to starch hydrolysis to increase starch loading and addition of enzymes (β -glucanase and hemicellulase) to reduce the mash viscosity. Since the oat mash contains sufficient quantities of assimilable nitrogen, addition of urea or other nitrogen sources may not be necessary, and this may offset some of the costs of viscosity-reducing enzymes.¹³ Development of high value-added coproducts will also help improve the process economics.

4.1.1.6 Rice

In terms of total production, rice is the third most important grain crop in the world behind wheat and corn. The total world production in 2005 was 622 million MT.⁵ Rice has several characteristics that make it a potential feedstock for fuel ethanol production. It has high starch content (Table 4.1), and the starch can be readily fermented to ethanol as demonstrated in the preparation of many alcoholic beverages in Asia. Rice hull and bran can easily be separated and removed from the grain to allow high starch loading in a fermenter. Rice bran contains several high-value nutraceuticals that can be recovered as valuable coproducts. Despite these advantages rice has not been seriously considered as a feedstock for commercial production of fuel ethanol. Although rice can be grown almost anywhere, even on very steep hillsides, its cultivation requires very large quantities of water for irrigation and its planting is a very labor-intensive process. In regions of Asia where labor cost is sufficiently low, virtually all the rice produced is used for food or exported. Even the broken grains generated in rice processing are used for human consumption. Thus, there will be no extra rice for fuel ethanol production in these regions. However, in more developed countries like the United States, damaged rice grains, which normally are wasted or used for animal feed, can be used to produce ethanol. One report estimated that wasted rice in North America can generate 170 million liters (45 million gallons) of fuel ethanol annually.¹⁴

4.1.2 Other Grains

There are other grains that can be used to make ethanol albeit in smaller quantities. One example is pearl millet. The total world production of pearl millet in 2005 was 15 million MT, which accounted for about 50 percent of total millet production. Pearl millet is planted on about 1.5 million acres in the United States. It can grow in arid conditions with very low rainfall (less than 300 mm) and can survive in areas where corn and sorghum suffer even total crop failure.¹⁵ Pearl millet contains about 70 percent starch, which gives it a theoretical ethanol yield of 0.43 L/kg. This grain is a good feedstock for ethanol production in areas where it is too hot or too dry for other grains to be cultivated.

4.1.3 Tubers and Roots

Root and tuber crops can be grown in the humid and subhumid tropics, which may not be suitable for cereal grains. Because of their high contents of starch they also are potential feedstocks for ethanol production. The two crops that have been given much attention are cassava and sweet potato.

4.1.3.1 Cassava

Cassava, which is also known as manioc, sagu, yucca, and tapioca, is one of the most important tropical root crops. It can survive drought extremely well and is particularly suitable for regions with low nutrient availability. It also does not require a lot of attention and hence is suitable for regions with a small labor force such as Africa. Africa and Asia lead the world in cassava production. Cassava production in Africa in 2005 was 118 million MT and accounted for 56 percent of the total world production, whereas Asia contributed 57 million MT or 27 percent of the total world production. Nigeria is the world's largest cassava producer. In 2005 41.6 million MT of cassava was produced in this country. This was more than triple the production 20 years earlier (12.1 million MT in 1985).⁵ Cassava used to be considered as a famine-reserve crop in Africa. It has recently emerged as the primary starch-based feedstock for future fuel ethanol production in Africa and Asia. Cassava typically contains 22 percent starch and has 70 percent moisture.¹⁶ Thus, on a dry basis it contains about 73 percent starch, which gives it a theoretical ethanol yield of 0.45 L/kg. Cassava starch can be easily hydrolyzed to sugars for production of fermentation-based products. In China cassava is considered as the alternate starch-based feedstock to replace corn in ethanol production. The Guangxi Zhuangzu autonomous region in southern China planned to complete construction of a plant to produce 139 million liters ethanol in 2007 and expand the capacity to 1.27 billion liters in 2010 using cassava as the primary feedstock.¹⁷ There also are proposals to build several ethanol plants using cassava in other countries, for example, Nigeria and Thailand. The government in Thailand recently approved a plan to construct 12 cassava ethanol plants with a total capacity of 1.24 billion liters/yr. These plants are expected to be in full