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Sorghum

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19 Sorghum

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19.1 INTRODUCTION

Energy security and greenhouse gas emissions reductions are perhaps now more than ever one of the most important priorities of many countries. Energy security is a growing concern because of uncertainties in supply coupled with sharp increases in prices due to geopolitical tensions and weather disturbances in oil-producing countries. In addition, maintaining a clean and healthy environment has also gained worldwide attention, even as the Intergovernmental Panel on Climate Change recently confirmed that human activities are to blame for global warming. To address these issues, many oil-importing countries have embarked on programs to develop alternative cost-effective but locally available, unconventional renewable energy sources that would reduce their dependence on oil, especially for transport, as well as minimize adverse impacts on the environment. Advances in technology have opened new opportunities for achieving some of these objectives.

Sorghum \( \text{Sorghum bicolor} \) \((L.)\) \text{Moench}\) is the fifth most important cereal crop worldwide (http://apps.fao.org/default.jsp) as well as an important source of feed, fiber, and biofuel (Doggett...
Sorghum, like maize and sugarcane, carries out C₄ photosynthesis, a specialization that makes these grasses well adapted to environments subject to high temperature and water limitation (Edwards et al. 2004). Sorghum is an important target of genome analysis among the C₄ grasses because the sorghum genome is relatively small (730 Mbp) (Paterson et al. 2009), the cultivated species is diploid (2n = 20), and the sorghum germplasm is diverse (Dje et al. 2000; Menz et al. 2004; Casa et al. 2005). As a consequence, numerous sorghum genetic, physical, and comparative maps have been constructed (Tao et al. 1998; Boivin et al. 1999; Peng et al. 1999; Klein et al. 2000, 2003; Haussmann et al. 2002; Menz et al. 2002; Bowers et al. 2003, 2005), a sorghum expressed sequence tag (EST) project (Pratt et al. 2005) and associated microarray analyses of sorghum gene expression have been carried out (Buchanan et al. 2005; Salzman et al. 2005), a comprehensive analysis of sorghum chromosome architecture has been completed (Kim et al. 2005), and an 8 × draft sequence of the sorghum genome (about twice the size of rice) has been completed by the U.S. Department of Energy Joint Genome Sequencing program (Paterson et al. 2009; http://www.phytozome.net/sorghum). In addition, genetic maps have been assembled at Texas A&M University and the University of Georgia (Menz et al. 2002; Bowers et al. 2003). The U.S. Department of Agriculture (USDA) germplasm system maintains 42,614 accessions, of which more than 800 exotic landraces have been converted to day length-insensitive lines to facilitate their use in breeding programs. In total, there are approximately 168,000 sorghum accessions held at repositories around the world. A set of mutation stocks developed by the USDA Plant Stress and Germplasm Development Unit in Lubbock, TX (Xin et al. 2008) is extensive enough to provide mutations in all of the genes in the sorghum genome. Such genomic tools, already in place, will greatly facilitate the introduction of traits required to optimize sweet sorghum for bioenergy production schemes.

### 19.2 BIOLOGY OF SORGHUM

#### 19.2.1 ORIGIN

The sorghum plant has undergone selection, domestication, and hybridization by humans to become a crop that can produce grain and forage in low-rainfall, high-temperature environments, thereby meeting the nutritional needs of people living in marginal areas. Vavilov (1951; cited by Mann et al. 1983), Snowden (1936; cited by Mann et al. 1983), Harlan and de Wet 1972, and Mann et al. (1983) have all theorized that Africa is the center of origin for sorghum. Although the exact location is debatable, domesticate can be attributed to the selection for sorghums without grain shattering to improve harvest ability (Mann et al. 1983). Early records of sorghum show its existence in India in the first century AD (Bennett et al. 1990), China in the 13th century (Undersander et al. 1990), and in the United States in the Seventeenth century (Agyeman et al. 2002). Currently sorghum is the fifth most important crop produced worldwide (Rooney and Awika 2004) and has widespread production in sub-humid and semi-arid regions in both tropical and temperate climates.

#### 19.2.2 CLASSIFICATION AND DOMESTICATION

Sorghum is a self-pollinating species consists of cultivated and wild species. *S. bicolor* subsp. *bicolor* (2n = 20) is the taxon that includes the agronomically important grain races bicolor, caudatum, durra, guinea, and kafir and ten intermediate races. Additionally, hybrid races can be identified from crosses among the basic races. There are more than 35,000 accessions of sorghum that are been maintained at the germplasm collection centers in the United States with similar numbers being maintained at the International Crops Research Institute for the Semi Arid Tropics (ICRISAT). The U.S. and ICRISAT collections have been evaluated phenotypically, and the USDA has developed a description list of more than 75 descriptors (http://www.ars-grin.gov/cgi-bin/npgs/html/desclist.pl?69). Very high levels of genetic diversity exist among and within races. Most U.S. sorghums are derived from Kafirn × milo crosses.
**Sorghum bicolor (L.) Moench**

Kingdom  
Subkingdom  
Superdivision  
Division  
Class  
Subclass  
Order  
Family  
Genus  
Species

## 19.2.3 Plant Description

Sorghum is a summer annual that is coarse and erect with much variability in growth characteristics. The culms are solid or sometimes with spaces in the pith, 0.6–5 m tall (Figure 19.1), depending on the variety and growing conditions. It is 5 to over 45 mm in diameter (Figure 19.2) and is either dry at maturity or has a sweet, insipid juice.

Vanderlip (1993) has defined the growth of the sorghum plant from emergence (stage 0) to physiological maturity (stage 9). The timing of various stages of development and the condition of the plant at each stage can be affected by soil fertility, insect or disease damage, water stress, plant population, and weed competition. As the total number of leaves increases and gives rise to a greater leaf area index, the growth rate of the sorghum plant increases. Leaves arise alternately at nodes along the stem and can be as much as 1 m long and 10- to 15-cm wide (House et al. 1995). Most leaf growth occurs between stages 3 and 5, when the upper eight to ten leaves develop (Vanderlip 1993). Leaves can number from 7 to 18 or more, and the total number is determined by the length of the vegetative period (Bennett et al. 1990). The flag leaf is the first leaf below the panicle and it holds the boot before extension. Flowering begins at the tip of the panicle and continues to the base, taking 4–5 days. Although primarily known as a self-pollinating crop, 2–20% cross-pollination can occur.

![Figure 19.1](See color insert)  
Sweet sorghum plants reach 450 cm in September 2007 at Lincoln, NE. The plants were rainfed and were grown in rotation with soybean.
occur, with higher percentages taking place from more open-headed panicles (House et al. 1995). Compared with the other two major spring planted crops, maize (*Zea mays*) and soybean (*Glycine max*), sorghum has the smallest seed (Vanderlip 1993). Sorghum kernels are generally spherical and range in weight from 20 to 30 mg (Hoseney 1994) and can be colored white, cream, pink, yellow, red, buff, brown, and reddish brown (Bennett et al. 1990). The kernels are covered by glumes, which can be black, red, brown, or straw. Most are colored. The sorghum kernel is made up of three major anatomical parts—the pericarp, germ, and endosperm—and each generally accounts for roughly 6, 10, and 84% of the kernel, respectively (Rooney and Serna-Saldivar 2000). The pericarp protects the kernel and is composed mostly of fiber; the endosperm is a major contributor to the kernel’s protein (80%), starch (94%), and 50–75% of B-complex vitamins; and the germ contains over 68% of the total mineral matter and 75% of the oil in the whole kernel (FAO 1995).

Sorghum leaves are broad and coarse, similar in shape to those of corn but shorter and wider. The blades of the leaves are glabrous and waxy. Sheaths encircle the culm and have overlapping margins. The panicle is erect, sometimes recurved, and is usually compact in most grain sorghums and more open in forage types. Prop roots may grow from culm nodes, and there is a bud at each node from which a tiller may grow. The seeds are white, yellow, red, or brown and are covered by glumes that may or may not be removed by threshing. It has a spikelet that contains two flowers, only one of which is usually fertile and sets a seed. When threshed, the seed separates from the floral bracts as in wheat, and the panicle has up to 6000 spikelets. The kernels are small with a round to conical shape. Seeds number at 25,000–61,740 per kilogram. Sorghum is most commonly red and hard when ripe, and it is usually dried after harvesting.

### 19.2.4 Adaptation

Temperature, day length, and water needs are three elements that affect sorghum adaptation and growth. Sorghum has the ability to produce a crop in areas with marginal rainfall and high temperatures, where other cereal grains often fail (Cothren et al. 2000), and is found from 40°S to 45° north latitude (Maunder 2002). Sorghum is more tolerant to high temperature (>38°C) and drought than most major agronomic crops. Sorghum is a warm-region crop that requires warm temperature for germination and growth. The optimum germination temperature is between 20°C and 25°C. Temperatures below freezing may kill the plants depending on stage of development. At early seedling stage (1–3 weeks), plants could recover after a short exposure to temperature

![Sweet sorghum stalks with different thickness ranges from 15 to 45 mm.](image-url)
of 5°C below freezing point; however, at temperatures lower than 5°C, plants are killed. Plants older than 3 weeks are more susceptible and may die at 0°C. The crop can grow where available water is between 360 and 500 mm and can respond positively to higher precipitation (Fribourg 1995). Sorghum can reduce its water losses by its heavy wax cuticle, curling of its leaves, and its relatively small number of leaf stomata (Gardner et al. 1981). When water supply is limited, sorghum has more efficient water transport system than either corn or cotton (Ackerson and Krieg 1977).

Sorghum has a fibrous root system that grows rapidly in deep soils, and it is efficient as a water forager. The adventitious root starts several weeks after emergence and extends rapidly up to 2 m depending on the depth of soil wetting (Sullivan and Blum 1970). Graser (1985) compiled seasonal water use of sorghum at several locations from 1976 to 1981 and reported a range of 179–540 mm under dry-land and 321–645 mm under irrigated conditions depending on the length of the growing season. Erie et al. (1981) reported that consumptive water use increases with plant growth, reaches a peak, and then decreases by harvest time. Water use of sorghum was found to be greatest during the boot and soft dough stage and lower during the seedling, tillering, and ripening stages (Porter et al. 1960). Several factors including temperature, precipitation, solar radiation, humidity, wind movement, and hybrid affect sorghum water-use efficiency. The water-use curve in any one year or at any site will vary from the long-term average because of changes in some of the factors listed above. Water-use efficiency ranging from 13 to 29 kg/ha per mm has been reported in the literature under dry-land and irrigated conditions (Hedge et al. 1976; Sivakumar et al. 1979). The crop has the ability to delay development under water stress during the vegetative growth stages and resume growth when water conditions improve. This drought avoidance mechanism works well under tropical and subtropical conditions with a long growing period. However, this mechanism of drought resistance may result in poor yield because of prolonged drought, insufficient season length, or when it occurs at critical growth stage. Field water capacities of 25–50% and temperatures above 28°C are most favorable for optimal sorghum germination (Fawusi and Agboola 1980). The favorable mean temperature for sorghum growth is approximately 37°C, and the minimal temperature for growth is 15°C (Cothren et al. 2000).

19.2.5 Crop Uses

Sorghum is one of the top five cereal crops in the world, along with wheat, oats, rice, corn, and barley. Worldwide more than 40 million ha are planted to sorghum. It is a genus with many species and subspecies, and there are several types of sorghum, including grain, forage, and sweet sorghums. Therefore, sorghum is extremely versatile in offering multiple pathways to ethanol.

- **Starch-to-ethanol**: Grain sorghum conversion to ethanol is equal to corn. Today, approximately 28% of the U.S. grain sorghum crop currently goes into ethanol production according to industry estimates.
- **Sugar-to-ethanol from sweet sorghum**: The conversion efficiency is similar to that of sugarcane.
- **Cellulosic ethanol**: No other crop or other cellulose source equals sorghum in conversion, production efficiency, or ethanol gallons per acre.

19.3 Grain Sorghums

Grain sorghums include what are commonly known as kafir, kafir corn, durra, and milo. Grain sorghum has been bred to produce approximately 2- to 5-ft height to facilitate harvesting with standard grain harvesters. Grain sorghum has a wide variety of uses that includes food for humans, feed for livestock, alcohol production, and industrial uses. Sorghum can be sorted into grain sorghums, forage sorghums, and sweet sorghums (Rooney and Serna-Saldívar 2000). Grain sorghums often are short and can be mechanically harvested whereas forage sorghums are tall and
provide fodder for livestock. The juice from sweet sorghums can be used to produce syrups and sugar or be fermented into alcohol. An estimated 40% of grain sorghum production worldwide is used for human consumption (Rooney and Waniska 2000). High-yielding white grain, tan-plant grain sorghum hybrids have developed an export market to Japan and other Asian countries for production of snack foods and beer because of their bland tastes, lack of gluten proteins, and genetically modified organism (GMO) traits. Gluten, the protein found in wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and rye (*Secale cereale* subsp. *Cereale*), is indigestible by people with celiac disease (Fasano and Catassi 2001). Sorghum grain can be milled into fractions of bran, germ, meal, flour, and grits of different sizes. The general methods of dry milling have been summarized by Hahn (Rooney et al. 1980) and Munck (1995). Sorghum flour can be used as a blend with wheat flour in baked products and has gained consumer acceptability (Munck 1995; Ragaee and Abdel-Aal 2006). In India and Africa, sorghum is used to make thin or stiff porridges and fermented beverages (Lochte-Watson et al. 2000) whereas in Central America and southern Mexico it is a total or partial replacement for maize in tortilla production (Almeida-Dominguez et al. 1991). A brewer using white food-grade sorghums and waxy sorghum grits can achieve reduced color, shorter conversion and runoff times, and improved yields for brewing (Figueroa et al. 1995).

Sorghum is being evaluated for use in health food supplements because of the presence of antioxidants, phytosterols, and policosanols in the germ and pericarp. Concentrated in the byproducts of milling and alcohol fermentation, these products might be in high enough quantities for commercial use. Sorghum oils have high levels of phytosterols (Singh et al. 2003) which reduce cholesterol absorption (Weller 2006), whereas sorghum wax contains policosanols, which reduce cholesterol production (Rooney and Awika 2004; Weller 2006). In the United States, sorghum is the second most important feed grain behind maize. The feeding value of grain sorghum for feed-lot cattle is 85–100% of maize (Kriegshauser et al. 2006) and 90–95% of maize for swine and poultry (Hulan and Proudfoot 1982). White-grain, tan-plant cultivars are ideal for feeding broilers because the absence of colored glumes reduces the amount of dark specks found on carcasses (Rooney and Waniska 2000). Hicks et al. (2002) reported that hybrids with heavy kernel weights had increased crude protein and fat content with reduced starch, which improved broiler chicken performance to be equal to or better than maize (Kriegshauser et al. 2006). Sorghum provides a source of starch for ethanol production in Nebraska and Kansas, and the byproducts have become important dairy and beef cattle feeds. In all countries except the United States, sorghum is used extensively as a cereal food. The grain is an excellent food source when ground into flour and used to make pancakes, porridge, and flatbreads. Sorghum grain produces edible oil, starch, dextrose, paste, and alcoholic beverages. Sorghum can be puffed, popped, shredded, and flaked to produce ready-to-eat breakfast cereals. Economically, the use of sorghum grits and commercial enzymes is also practical. In the United States, sorghum is used primarily as a corn substitute for livestock feed because their nutritional values are very similar. Some hybrids commonly grown for feed have been developed to deter birds therefore contain a high concentration of tannins and phenolic compounds, which causes the need for additional processing to allow the grain to be digested by cattle. In arid regions in less-developed regions of the world, sorghum is an important food crop especially for subsistence farmers.

### 19.3.1 Grain Sorghum as a Source of Ethanol

Researchers and ethanol producers have shown that grain sorghum is a good feedstock for ethanol that is comparable to that from corn grain and could make a larger contribution to the nation’s fuel ethanol requirements. However, in the past, factors affecting ethanol yield were less well studied for sorghum than for corn. Little research has been conducted on performance of sorghum varieties in ethanol fermentation. Several researchers have investigated the digestibility of sorghum starch and sorghum protein (Duodu et al. 2003; Selle et al. 2010; Wong et al. 2009) as related to its use in feed or food. Others have investigated the isolation of sorghum starch and its properties (Park et al. 2006; Sang et al. 2008). The economic viability of an ethanol production facility depends on several
Sorghum factors, including ethanol yield, efficiency of conversion, and quality of the “distiller’s grain” (grain residue and yeast mass remaining after the fermentation process).

Sorghum has the potential for being used in the production of bioindustrial products, including bioethanol. Sorghum is a starch-rich grain with similar composition to maize, and, as with all cereals, its composition varies significantly because of genetics and environment (Rooney and Serna-Saldívar 2000). Starch ranges of 60–77% and 64–78% have been reported for sorghum and maize, respectively (Shelton and Lee 2000). As such, sorghum grain would be appropriate for use in fermentation similar to the use of maize for the production of bioethanol. Its use may be of particular benefit in countries where rainfall is limiting and maize does not grow well. With regard to the United States, approximately 95% of the bioethanol is currently produced from maize starch, primarily in the maize-growing regions. Sorghum production in the United States in 2004 was 11.6 million t (http://faostat.fao.org), equivalent to approximately 457 million bushels, and 10–20% of those were used for ethanol production (http://www.sorghumgrowers.com). In the same year in the United States, 3.4 billion gal of ethanol were produced from 1.22 billion bushels of grain (http://www.ksgrains.com/ethanol/useth.html). From this, it may be calculated that 1.2–2.3 million metric t sorghum was used for ethanol production, 3.7–7.5% of the grain for ethanol production was sorghum, and 0.13–0.25 billion gal of ethanol originated from sorghum. Although significant research into the production of ethanol from maize grain has been conducted, comparatively little research has been done on the conversion of sorghum grain into bioethanol.

19.4 FORAGE SORGHUMS

Forage sorghum differs from grain sorghum primarily in utilization. Forage sorghum is an important annual forage source in the Midwestern and Plains regions of the United States and can be planted later than maize (Z. mays L.) to provide fodder for stock between late spring and autumn. The crop may be cut only once (single cut) or several times (multicut) during the growing season, whereas maize can be cut only once. It uses water more efficiently, yields greater biomass, and provides an acceptable yield when exposed to drought. These include sudan grass and tunis grass and are used for pasture and forage. Forage sorghums ranged from 2- to 5-m tall, and whole-plant yields ranged between 3.1 and 10.1 t of dry matter per acre. They are annuals and grow quickly. They are generally used for summer pasture. Johnson grass, perennial grass sorghum, is considered a pest when out of control, but it makes an excellent hay and cattle feed. It is important to remember that forage-sorghum varieties vary widely with respect to agronomic characteristics.

Sweet sorghum is one of the many types of cultivated sorghum, characterized by the high sugar content in its stem juice. Some lines attain juice yields of 78% of total plant biomass and contain 15–23% soluble fermentable sugar (comparable to sugarcane). The sugar is composed mainly of sucrose (70–80%), fructose, and glucose. Most of the sugars are uniformly distributed in the stalk, whereas approximately 2% are in the leaves and inflorescences (Vietor and Miller 1990). Even in dry climates, sweet sorghum can yield high levels of fermentable sugars, together with grain and lignocellulosics (Gnansounou et al. 2005). Stalks of sweet sorghum contain fermentable sugars capable of producing 400–800 gallons of ethanol per acre (Reddy et al. 2008), which is comparable to ethanol yield from corn grain (assuming an average irrigated corn yield of 170 bushels/acre results in 470 gal of ethanol); however, the conversion of sweet sorghum into ethanol does not require the energy-intensive steam cooking step necessary to produce ethanol from corn grain.

Sweet sorghum reproduces by seed and produces tillers, but it has no rhizomes. It is a perennial grass under tropical conditions, but it is winter-killed in areas where frost occurs. Some sweet sorghum cultivars are grown for syrup production, whereas others are grown for forage (silage). Sweet sorghum is adapted to widely differing climatic and soil conditions, rendering it ideally suited as a biofuel crop for marginal land production. Utilization for bioenergy conversion processes is higher for sweet sorghum compared with other crops because it produces high biomass, fermentable carbohydrates yields, and a small amount of grain.
19.5 **SWEET SORGHUM AS A BIOENERGY CROP**

Sweet sorghum yields high levels of fermentable sugars, together with grain and lignocellulose. Hunter and Anderson (1997) indicated that the sugar produced in sweet sorghum has a potential ethanol yield up to 8000 L/ha, or about twice the ethanol yield potential of maize grain. In addition to producing large amounts of sugar-rich biomass, hybrids can be developed from crosses between grain-type seed parents and sweet-type pollen parents (Hunter and Anderson 1997). The product of these crosses typically increase biomass yields and sugar content when compared with the original grain-type seed parents. Such hybrids can co-produce grain at levels approaching the yields of the grain-type seed parent (Miller and McBee 1993).

Sweet sorghum has already been identified as a preferred biomass crop for fermentation into methanol and ethanol fuel. Its processing takes ethanol and its derivatives from the direct fermentation of sugars present in the stem juices, followed by processing of the bagasse (the remaining part of the stems after juice extraction), to pyrolytic oils, quality fuels, pellets of carbon, synthesis gas, and lignocellulosic materials. An alternative energetic application of the bagasse may be electricity production through combustion of total biomass. In addition, the stillage from sweet sorghum, after extraction of juice, has a higher biological value than the bagasse from sugarcane when used as fodder for animals because of higher levels of micronutrients and minerals. It is also processed as a feed for ruminant animals. Apart from these, the stillage contains levels of cellulose similar to those in sugarcane bagasse, suggesting that it has good potential as a raw material for pulp products.

Sweet sorghum offers several important advantages for bioenergy; remarkable drought tolerance, productivity as a hybrid crop, amenability to genetic transformation, and extensive genomic resources available for its study. Because of its high yield in biomass and fermentable sugars, sweet sorghum can be converted into energy carriers through one of two pathways: biochemical and thermochemical. Through biochemical processes, the crop sugars can be converted to biofuels (ethanol, butanol, and hydrogen). Thermochemical processes such as combustion and gasification can be used for the conversion of the sweet sorghum bagasse to heat and electricity (Table 19.1). Pulp for paper, compost, and composites materials are some other products that can also be derived from sweet sorghum bagasse.

Sorghum’s adaptation to drought stress allows it to grow in some of the world’s less favorable climates. Morphological and physiological responses under drought stress make this plant unique among the cereals. Sorghum’s capacity to fold (rather than roll) its leaves and the deposition of a heavy layer of wax over the leaves reduce evapotranspiration. The root system of sorghum is bigger.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Carbon</th>
<th>Nitrogen</th>
<th>Sulfur</th>
<th>Ash</th>
<th>HHV (Btu/lb)</th>
<th>Total Biomass (Mg/ha)</th>
<th>Ethanol (gal/ha)</th>
<th>Total Land to Produce 35 Billion Gal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical maize</td>
<td>49.00</td>
<td>0.97</td>
<td>0.09</td>
<td>4.78</td>
<td>8058</td>
<td>35.0</td>
<td>3500</td>
<td>10.0a</td>
</tr>
<tr>
<td>Silage corn</td>
<td>47.42</td>
<td>0.58</td>
<td>0.05</td>
<td>6.84</td>
<td>7718</td>
<td>11.0</td>
<td>1100</td>
<td>31.4</td>
</tr>
<tr>
<td>Bioenergy millet</td>
<td>49.18</td>
<td>0.56</td>
<td>0.08</td>
<td>4.02</td>
<td>8161</td>
<td>36.0</td>
<td>3600</td>
<td>9.7</td>
</tr>
<tr>
<td>SS M 81 E</td>
<td>46.97</td>
<td>0.35</td>
<td>0.08</td>
<td>4.50</td>
<td>8031</td>
<td>35.0</td>
<td>3500</td>
<td>10.0</td>
</tr>
<tr>
<td>Switch grass</td>
<td>42.00</td>
<td>0.59</td>
<td>0.10</td>
<td>7.09</td>
<td>7590</td>
<td>10.4</td>
<td>1040</td>
<td>33.7</td>
</tr>
<tr>
<td>Corn stover</td>
<td>43.60</td>
<td>0.83</td>
<td>0.09</td>
<td>6.90</td>
<td>7782</td>
<td>7.4</td>
<td>740</td>
<td>47.2</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>41.00</td>
<td>0.39</td>
<td>0.09</td>
<td>5.65</td>
<td>7750</td>
<td>28.0</td>
<td>2800</td>
<td>12.5</td>
</tr>
</tbody>
</table>

SS, sweet sorghum; HHV, high heating value.

*a* Million hectares.

---

**TABLE 19.1**

Chemical Analysis, Burning Profile, Biomass Production, Potential Ethanol, and Total Land Needed for Different Bioenergy Crops to Reach the 35 Billion Gal U.S. Reachable Goal
Sorghum and deeper than that of maize. Sorghum plants have a capacity to remain relatively inactive during drought and renew growth when conditions are favorable (Doggett 1988). Because sorghum grown for biomass can be harvested before it is fully mature, it is possible to grow it in a double crop sequence with a winter annual legume. Winter annuals are planted in the fall, grow rapidly in the spring, and reach harvest anytime during late spring to early summer. Sorghum, which is well adapted to germination under limited moisture, can be no-till planted into the stubble of a winter annual crop. The primary advantages of a double crop sequence are to maximize use of solar radiation, provide winter cover against wind and water erosion, and increase biomass per hectare yields (Karpenstein-Machan 2001). Because sorghum and winter annuals have differing cardinal temperatures for growth, the double crop sequence can take advantage of a longer growing season than either crop alone.

Given that water availability is poised to become a major constraint to agricultural production in coming years, cultivation of corn becomes difficult. Sweet sorghum would be a logical crop option in lieu of corn in such situations. Sweet sorghum can be grown with less irrigation, rainfall, and inputs compared with corn. In addition to sweet stalk, grain yields of 2–6 t/ha (which can be used as food or feed) could be harvested from sweet sorghum.

A wide range of maturity classes is required to extend the harvest period to meet the requirements of the processing factories. Sweet sorghum’s energy-savings and value emerge in several ways.

- The crop only needs 12–15 in. of rain during the growing season to make a crop; therefore, it is suitable for dry-land production or under limited irrigation. If the crop receives more moisture, it will respond positively.
- It requires only 40–60 lb of nitrogen per acre. The crop is long-rooted and can extract residual nitrogen left by previous crops or from nitrogen-fixing soybeans proceeding in rotation.
- Sweet sorghum juice does not require the long fermentation and cooking time needed to process corn ethanol.
- Some of the crop residue left after juice extraction (called bagasse) can be dried and burned for fuel ethanol distillation. These residues can also be used for animal feed, paper, or fuel pellets.
- The crop need not be grown on a farmer’s best land which allows farmers to make use of poorer ground.
- The simplicity of ethanol production from sweet sorghum could lend itself to on-farm or small-cooperative efforts at fuel-making.
- Ethanol plants in the state could choose, with some additional equipment, to make seasonal runs of sweet sorghum juice.

### 19.6 COMPARISON TO OTHER BIOENERGY CROPS

Sorghum is relatively inexpensive to grow to obtain high yields (Chiaramonti et al. 2004). It can produce approximately 30–50 dry Mg/ha of biomass per year on low-quality soils with minimal inputs—fertilizer and water per dry ton of crop. When compared with the input requirements of other crops, sorghum requires half of those needed by sugarbeets, and one-third of the requirements of sugarcane or corn (Soltani and Almodares 1994; Renewable Energy World 2000). Sweet sorghum juice is ideally suited for ethanol production given its higher content of reducing sugars compared with the content of other sources, including sugarcane juice. These important characteristics, along with suitability for seed propagation, mechanized crop production, and ethanol production capacity comparable to sugarcane molasses and sugarcane, make sweet sorghum a viable alternative raw material source for ethanol production. Furthermore, after the extraction of juice, sorghum stover can be used as a fuel for ethanol distillation. The remaining stover can be used as fodder for animals or for additional ethanol production through lignocellulose digestion. It can out-produce most other cereals.
under marginal environmental conditions, especially under hot and dry conditions. Furthermore, sweet sorghum is frequently grown in environments that are normally too harsh for other C₄ plants.

Also important is the amount of energy used to produce ethanol. Historically, for each unit of energy it took to plant and harvest a crop and process it into ethanol, the fuel returned 0.92 units of energy. Ethanol had a negative “energy balance” of 1 unit in for 0.92 units out (1:0.92). However, steady improvements have been made in corn yield, harvesting, and ethanol processing efficiency. The latest studies show corn ethanol boasts a positive energy balance of 1:1.25—a 25% net increase in net energy (Farrell et al. 2006). Today, corn ethanol is made by converting the starch in corn to sugars and then into alcohol by a fermentation process. Sugarbeets (Beta vulgaris L.) are a better ethanol source, producing nearly 2 units of energy for every unit used in production. However, sugarcane is by far the most efficient of the current feedstocks, yielding more than 3 units as much energy as is needed to produce the ethanol derived from it (Hopkinson and Day 1980). Sweet sorghum’s positive energy balance, with a ratio of 1:3, is comparable to that of sugarcane (Worley et al. 1992). Given their positive energy balances and higher yields, it makes more sense to produce ethanol from sugar crops than from starchy grains.

Switchgrass (Panicum virgatum) has gained a great deal of attention as a biomass crop in North America. However, establishment issues and relatively low annual dry matter yields suggest other crops may be better suited for cellulosic ethanol production in Iowa, Nebraska, and the surrounding states. There have been multiple reports of switchgrass biomass yields from the north-central U.S. states. Second-year switchgrass dry matter at four Nebraska locations was 1.6–7.3 Mg/ha (Schmer et al. 2006). Annual yields of fully established switchgrass swards were 13–21 Mg/ha at Mead, NE and 6.5–11.0 Mg/ha at Arlington, WI (Casler et al. 2004). Switchgrass dry matter yields at Ames, IA were 4.5–14.3 Mg/ha depending on the genotype (Hopkins et al. 1995). Biomass production on Conservation Reserve Program land in South Dakota totaled 3–4 Mg/ha with 56 kg N/ha (Mulkey et al. 2006). Biomass yields of switchgrass fertilized with 120 kg N/ha and harvested at maturity stages R3–R5 averaged 10.5–11.2 Mg/ha at Mead, NE and 11.6–12.6 Mg/ha at Ames, IA (Vogel et al. 2002). The average dry matter yield of 20 switchgrass populations grown in southern Iowa was 9.0 Mg/ha (Lemus et al. 2002). In comparison, final dry matter yields of grain-type winter triticales in Iowa were 8–16 Mg/ha with no more than 33 kg N/ha (Schwarte et al. 2005).

19.7 VARIETIES OF SWEET SORGHUM

Variety selection is an important decision in sweet sorghum production. Improved varieties have been developed in recent years at the U.S. Sugar Crops Field Station near Meridian, MS. Seed of older varieties originating at other places may still be available in some areas. Important varieties are described (Table 19.2).

19.8 BIOENERGY-RELATED TRAITS

19.8.1 FLOWERING AND MATURITY

Sorghum is a short-day species and requires short days (10–11 h) and long nights to stimulate the reproduction phase. Quinby (1967) reported that four genes influenced inheritance of duration of growth in sorghum. Manipulation of delayed flowering is an important trait to obtain a higher total biomass. Photoperiods longer than 11 h promote the vegetative growth. Most U.S. collection is sensitive to the photoperiod. Efforts were made in the early 1960s in Texas to convert more than 500 unique sorghum lines to photoperiod-insensitive lines to enhance the genetic variability. Grain sorghum requires less water than corn, under low to modest yield conditions, and it is an alternative to corn in production environments with frequent severe water deficits (Carter et al. 1989; Bennett et al. 1990; Maman et al. 2004; AFRIS-FAO 2006; Wikipedia 2006).
<table>
<thead>
<tr>
<th>Cultivar/Line</th>
<th>Days to Anthesis</th>
<th>Plant Height (cm)</th>
<th>Brix Reading</th>
<th>Wet Stalk (g/stalk)</th>
<th>Dry Stalk (g/stalk)</th>
<th>Stalk Moisture (%)</th>
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<td>70.93</td>
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<td>66.09</td>
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<td>386.00</td>
<td>125.00</td>
<td>67.67</td>
</tr>
</tbody>
</table>

(Continued)
Sweet sorghum may grow to 3–5 m tall. Height is desirable because it influences total biomass. There is a strong correlation between photoperiodism and plant height. The longer the plant remains in the vegetative stage, the greater the number of nodes and leaves. There are four unlinked genes that affect the total number of internodes. These genes exhibit partial dominance and were designated $dw_1$, $dw_2$, $dw_3$, and $dw_4$. Several studies have identified and mapped quantitative trait loci (QTL) that affect plant height using recombinant inbred populations (Lin et al. 1995; Pereira and Lee 1995). The map locations of these QTL seem to be similar in maize and sorghum and indicated that possible homologies exist with maize QTL and mutations known to affect plant height.

### 19.8.3 Lignin Concentrations

Lignin concentration is an important component in any bioenergy crop. In sweet sorghum, both high and low lignin level lines could be utilized. Low lignin lines are suitable feedstock for cellulosic-based ethanol, whereas high lignin lines are desirable for co-firing to produce electricity. Brown midrib mutation in cereals affects lignin level. The brown midrib ($bmr$) mutations were first discovered in corn 1926. Early studies revealed the trait resulted in lower fiber and lignin within the plant and could increase the conversion efficiency of sorghum biomass for lignocellulosic bioenergy. In sorghum, more than 19 $bmr$ mutants were discovered by Porter et al. (1978). The $bmr$ mutants are characterized by the reddish-brown coloration of the vascular tissue of the leaf blade, leaf sheath, and stem that is associated with alteration of secondary cell wall composition, especially lignin. Because of the development of biocatalysts (e.g., genetically engineered enzymes, yeasts, and bacteria), it is possible to produce ethanol from any plant or plant part containing lignocellulose biomass, including cereal crop residues (stovers). Sorghum stover also serves as an excellent feedstock for ethanol production. Stover contains lignin, hemicellulose, and cellulose. The hemicellulose and cellulose are enclosed by lignin (which contains no sugars), making them

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**TABLE 19.2 (Continued)**

Brix (Sugar Content) and Other Biomass-Related Trait Values of Sweet Sorghum Cultivars/Lines

<table>
<thead>
<tr>
<th>Cultivar/Line</th>
<th>Days to Anthesis</th>
<th>Plant Height (cm)</th>
<th>Brix Reading</th>
<th>Wet Stalk (g/stalk)</th>
<th>Dry Stalk (g/stalk)</th>
<th>Stalk Moisture (%)</th>
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<td>13.40</td>
<td>138.67</td>
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<td>305.00</td>
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difficult to convert into ethanol, thereby increasing the energy requirement for processing. The *bmr* mutant sorghum, pearl millet (*Pennisetum glaucum*), and corn lines have significantly lower levels of lignin content (51% less in their stems and 25% less in their leaves). Purdue University research showed 50% higher yield of the fermentable sugars from the stover of certain sorghum *bmr* lines after enzymatic hydrolysis. Therefore, the use of *bmr* cultivars would reduce the cost of biomass-based ethanol production. The *bmr* crop residues have higher rumen digestibility and palatability, making them also good for fodder.

### 19.8.4 Seedling Cold Tolerance

As a C₄ tropical crop species, most sorghum lines are susceptible to chilling stress during early-season planting, and tolerance to early-season cold temperatures is a major trait that is needed in many of the sorghum production areas of the United States. Stand establishment of sorghum is adversely affected by air and soil temperature below 15ºC at germination, emergence, and early seedling growth. Partial credit for a broader range of adaptation for maize can be given to breeding efforts for improved seedling cold tolerance. Similar improvement in sorghum would allow for expansion of this crop into cooler climatic regions. The University of Nebraska holds an extensive, highly variable collection of over 500 lines of sweet sorghum. Cold-tolerant germplasm could serve to expand the geographical range of sorghum cultivation and minimize the inherent risks involved in early-season planting of sorghum within production areas. Additionally, an earlier sowing date offers growers the option of capitalizing on higher levels of available soil moisture and lower evapotranspirative demands in the early spring, potentially serving as a drought-avoidance strategy. Early planting of the crop within the Midwest would allow for multiple harvests. For example, in Nebraska, cold-tolerant sweet sorghum has been planted on April 15, harvested in early August (22 Mt/ha of dry biomass) and the ratoon crop harvested (12 MT ha⁻¹) in mid October. The ratoon crop alone equals a full season harvest of 1 ha of switchgrass. Improved seedling cold tolerance has been attributed to seedling vigor and greater biomass (Cisse 1995).

### 19.8.5 Sugar Yield

Sweet sorghum is one of the many types of cultivated sorghum and is characterized by high sugar content in the juice of the stem. Some lines attain juice yields of 78% of the total plant biomass comprised of 15–23% soluble fermentable sugar. The sugar is composed mainly of sucrose (70–80%), fructose, and glucose. Most of the sugars are uniformly distributed in the stalk, whereas approximately 2% are in the leaves and inflorescences (Vietor and Miller 1990). The wide range of variability in soluble solids (brix; 15.5–24.9) and sucrose percentage (from 7.2 to 15.5%) indicates the high potential for genetic improvement to produce high sweet-stalk yield coupled with high sucrose percentage sweet sorghum lines. In an early study, Ayyangar et al. (1936) in crosses between gain and sweet sorghum suggested that a single dominant gene controlled the nonsweet phenotypes. A more recent study (Li et al. 2004) suggested that more than one gene with a dominant effect control the level of sugar in the stalks. Genotypic differences for extractable juice, total sugar content, fermentation efficiency, and alcohol production have also been reported. The predominant role of nonadditive gene action total soluble solids, millable sweet-stalk yield, and extractable juice yield indicates the importance of breeding for heterosis for improving these traits.

### 19.9 Sorghum Juice Harvest Scenario

The options for harvesting sorghum include removing the whole or chopped stalk or pressing the sugar-rich juice in the field and removing only the juice or the juice and pressed stalk. Chopped stalks can be collected with traditional forage harvesters that are readily available and can be easily
adapted to harvest sweet sorghum. The primary advantage of this approach includes the rapid loss of moisture in the first 24 h after chopping. In-field juice harvesters expel the sugar-rich juice during harvest and can thus eliminate the cost of transporting stalk material. This approach may also permit the use of low-cost, on-farm fermentation as an alternative to large-scale processing/fermentation facilities. A prototype juice harvester has been successfully demonstrated with sweet sorghum varieties. The juice needs to be extracted to reduce the cost of transportation and speed-up the drying of the stalks. The stalks contain from 40 to 50% moisture after extraction, depending on the efficiency of the extraction process. The disadvantage of extracting the juice before burning is that it reduces the Btu per pound by approximately 5–8%.

19.9.1 Factors Affecting Juice Production

Sugar content was highest in the middle of the plant stalk for sweet sorghum (Janssen et al. 1930). The top 300–450 mm of the stalk could be removed without significant loss of juice and sugar. Plants expressed 3 days after harvest and stripped of their leaves had higher sugar contents in the juice than those expressed immediately after harvest (Janssen et al. 1930). Other experiments have shown that juice yields decreased and sugar contents increased for sweet sorghum stalks stored 48 h between harvest and expression (Broadhead 1972). The change in sugar content and juice yield after storage was attributed to evaporation of water from the plant in both cases. Juice yields from plants are also affected by the amount of moisture in the soil (Janssen et al. 1930). The amount of solar radiation received by sweet sorghum is responsible for 75% of the variation in plant crop yield (Hipp et al. 1970). The top 300 juice yields from plants are also affected by stalk, and juice yield increased linearly as the amount of solar radiation received between the boot and early seed formation stages increased. Row spacing had a highly significant effect on the fresh mass of the stalk and total plant of Rio variety sweet sorghum. Fresh plant mass yields were higher for narrow row spacing. Sweet sorghum planted in a narrow-row spacing had a greater leaf area compared with wide row spacing (Wortmann et al. 2010).

19.9.2 Potential Uses of Sweet Sorghum Juice

There are a number of uses of sweet sorghum juice:

1. Sweet sorghum syrup has been produced in the United States since colonial days. Some sweet sorghum syrup has at one time or another been produced in every one of the contiguous 48 states. Sweet sorghum is grown extensively for syrup production in the southeastern states. Kentucky is one of eight states in the Southeast and Midwest producing approximately 90% of the total U.S. output. Excellent quality syrup could be made when the brix of raw juice was at least 14°C, which was more or less throughout the year. The prepared syrup generally has a final brix of 70–75°C (corresponding to syrup temperatures of approximately 106°C) and a minimum shelf-life of 6–9 months.

2. Ethanol can be produced from sweet sorghum juice using yeast. Immediately after harvesting, the fermentation process must begin. Fermentation can take place in large storage containers in the environment without temperature control.

3. Sweet sorghum juice could be returned back to the soil to provide nutrients. Each 1000 gal of juice contain 10 lb of nitrogen, 10 lb of potassium, and 10 lb of phosphorus, in addition to micronutrients.

19.10 Conclusions

*S. bicolor*, a diploid, has a relatively small genome (735 Mbp), which although larger than rice (389 Mbp) is smaller than the other important cereals (wheat 16,900 Mbp and maize 2600 Mbp). The last genome duplication event for the *S. bicolor* genome seems to have occurred much earlier than
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the divergence of the major cereal crops from a common ancestor. Completion of the whole genome sequencing project in 2009 will exponentially increase the sequence data available for Sorghum spp. and will provide valuable information on cereal domestication in the African continent, an event that appears to have occurred independently of other continents although by similar reinforced selective pressures. In a way, sorghum genome sequencing will close a biographic triangle into the knowledge of the polymorphism shared before the divergence of these important grasses and ultimately in the understanding of the evolution in cereals crops among Africa, the Americas, and Asia. The tenets of colinearity and microlinearity of grass genomes mean that our knowledge of other cereals and their evolutionary ties will also greatly improve. Because of their economic and scientific value, cereal genomes have been studied over the last 15 years using highly advanced technologies. The similarity at the DNA level makes it possible to use comparative genetics to look for particular genes of unknown sequence among the genomes with the aim of using that information to develop new varieties or discovering new genes that could have a potential impact on traits that are of global importance (e.g., food quality and drought resistance).

Sweet sorghum has long been known to be an excellent source of sugar which can easily be fermented and distilled into fuel-grade ethanol. The main factor keeping sweet sorghum from competing with corn as a fuel crop is the lack of an established production method. Mechanically harvesting sweet sorghum requires either a specialized harvester capable of extracting the sugary juice from the stalks in the field or a modified sugarcane harvester and a large nearby pressing facility. The juice must be quickly fermented to prevent degradation of the sugars in the juice. Also, the costs associated with transportation of the crop to the mill will be the major limiting factor for where sweet sorghum can be profitably grown. Varieties that have higher sugar contents per ton of biomass will be more efficient to process and haul to the mill.

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