Assessing sorghum [*Sorghum bicolor* (L) Moench] germplasm for new traits: food, fuels & unique uses

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Abstract

Sorghum [*Sorghum bicolor* (L) Moench] is the fifth most important cereal crop in the world; however, it has a wide range of other applications that are being explored with worldwide interest in renewable resources. The USA sorghum germplasm collection contains over 41,000 accessions that represent landraces and cultivars from over 115 countries. Traditionally, this collection has been evaluated for such traits as abiotic or biotic stress and other agronomic characteristics and little work has been done on the collection to characterize it for what might be considered "non-traditional" uses. Sorghum is a gluten-free cereal and recent research has begun to evaluate it for flour characteristics that would make it more amenable to baking and other processing technologies. New technologies are allowing sorghum germplasm to be screened for high levels of anti-oxidants that show promise in cancer research and glycemic control. In Europe, broomcorns continue to be grown for a unique market. Most recently, various forage accessions have been evaluated for their potential for renewable fuel production. Near infrared technologies have been developed to quickly and cost-effectively screen large numbers of accessions for such compositional characteristics as ash, lignin, glucan, xylan, galactan, and arabinan, all of which have unique properties related to various bioconversion technologies. Given its genetic variability, a known genomic sequence, and a robust seed industry, new utilization of sorghum within the health food market, niche utilization markets and the bioenergy arena make sorghum an attractive renewable resource for future generations.

Keywords: sorghum, flour characteristics, anti-oxidants, renewable fuel, near infrared technologies

Introduction

Sorghum [*Sorghum bicolor* (L) Moench] is valued for its grain, stalks and leaves. It is one of the World's major cereal crops. Worldwide, there are a small number of grains that supply approximately 85% of the world's food energy and only four other foods (rice, wheat, maize, and potatoes) are consumed more than sorghum. For 500 million people in over 30 countries of the semi arid tropics, sorghum is a dietary staple.

Sorghum is used not only for human food, but also for fodder and feed for animals, building material, fencing, or for brooms (Doggett, 1988; House, 1985; Rooney and Waniska, 2000). In the USA, sorghum grain has traditionally been used for livestock feed and stems and foliage for green chop, hay, silage, and pasture. Some people in the USA are familiar with sorghum for the syrup made from the sweet juice pressed from stalks of certain sorghum varieties. In Europe, however, there is very little production of sorghum (Berenji, 1991; Berenji and Dahlberg, 2004). Though sorghum is not used routinely in Europe, it has been around for many centuries as highlighted by paintings of sorghum in festoons found in the villa Farnesina from the late 1700s.

The aim of this paper was to review the most important aspects of sorghum germplasm, cultivation and utilization with special reference to novel uses such as food and fuels and to its cultivation and use in Europe (Berenji and Sikora, 2004; Dahlberg and Berenji, 2011; Sikora and Berenji, 2005).

Botanical classification of sorghum

Several authors have discussed the systematics, origin, and evolution of sorghum (de Wet and Harlan, 1971; de Wet and Huckabay, 1967; Harlan, 1975; Snowden, 1936). Dahlberg (2000) provides an excellent overview of the present-day classification using an integrated classification system to describe the variation found within cultivated sorghums.

Sorghum is classified under the genus Sorghum (Clayton and Renvoize, 1986). De Wet (1978) recognized *S. bicolor*, representing all annual cultivated, wild and weedy sorghums along with two rhizomatous taxa, *S. halepense* and *S. propinquum*. *Sorghum bicolor* was further broken down into three subspecies: *S. bicolor* subsp. *bicolor*, *S. bicolor* subsp. *drummondii*, and *S. bicolor* subsp. *verticilliflorum*. Cultivated sorghums are classified as *S. bicolor* sub-

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sp. *bicolor* and are represented by agronomic types such as grain sorghum, sweet sorghum, sudangrass and broomcorn (Berenji and Dahlberg, 2004). Additionally, there are at least two weedy sorghums widespread in temperate zone, i.e. Johnsongrass and spontaneous sorghum (shattercane) (Figure 1).

Johnsongrass (*S. halepense*), a close relative to cultivated sorghum, is known as one of the worlds worst weed. It reproduces through both seed and rhyzome production and is considered a major perennial weed in many of the crops in the world. Control of this weedy sorghum is both time consuming and difficult.

In Europe there are at least two distinct areas (SE Hungary and NE Serbia) where spontaneous sorghum (shattercane) has been reported. The term spontaneous refers to the nature of dispersal of this weed through shattering of seeds as well as to its most probable origin by out-crossing between cultivated S.bicolor and the weedy *S. halepense*. Horizontal gene flow between cultivated and weedy sorghums presents unique problems in sorghum for use in biotechnology research (Sikora and Berenji, 2008b).

Origin of sorghum

Sorghum is an ancient crop. Mann et al (1983) indicated that the origin and early domestication of sorghum took place in northeastern Africa north of the Equator and east of 10°E latitude, approximately 5,000 years ago. However, carbonized seeds of sorghum with consistent radiocarbon dates of 8,000 years BP have been excavated at an early Holocene archaeological site at Nabta Playa near the Egyptian-Sudanese border (Wendorf et al, 1992; Dahlberg and Wasylikowa, 1996). These sorghums are 3,000 years older and 10-15° latitude further north than had been previously reported and suggests an early interest in sorghum by hunter and gathers and early agriculturalists. These early domestication events followed major trading and migratory paths of early Africans and Asians. As these early domesticated sorghum spread throughout Africa and Asia, plants were selected and dispersed throughout a broad range of environments and utilization giving rise to a widely adapted genetic base that has been further exploited throughout the agricultural process to create the current crop known as cultivated sorghum.

Broomcorn is a specialized type of cultivated sorghum grown mainly outside Africa. In fact, broomcorn was the sorghum type which was first cultivated and utilized in Europe and America, previous to all the other cultivated sorghums introduced later directly or indirectly from Africa (Franklin, 1757; Doggett, 1988). The origin of broomcorn in Europe is believed to be the Mediterranean region, more precisely Italy. Becker-Dillingen (1927) made notes on broomcorn grown in the Piedmont region of Italy as early as 1204. The widespread distribution of broomcorn in Italy is dated to the end of 17th century when Bauhini (1658) states that the slender and very rigid dried sorghum heads were made into brooms by the Italians and used for brushing clothing in Italy, France, and also Germany. Ray in 1688 (cit. Washburn and Martin, 1933) gives a full discussion of sorghum and records the use of the plant, stating that he himself had seen corn brooms on sale in Venice, Italy. At the beginning of the sixteenth century broomcorn started to spread from Italy to the Danube River Basin region, moved into the Austro-Hungarian Empire, and reached the Pannonian Plain most probably in the eighteenth century (Sávoly, 1921). Körnicke (1885) mentioned "*sorghum technicus*" as being widely produced in Croatia, Hungary and Italy. There are documents bearing witness that broomcorn had been grown in Northern Serbia in the 1860s. By the 1700s, broomcorn's widespread use in Europe had attracted the interest of Benjamin Franklin, who first documented its utilization in the United States in a letter to Samuel Ward on March 24, 1757 (Martin and Leonard, 1949).

Sorghum germplasm

Sorghum germplasm is unique, not only in its size, but also in its diversity (for a review of some of the larger collections see: Dahlberg and Spinks, 1995; Prasada et al, 1995; Wenzel, 1995). Unique germplasm collection of broomcorn is maintained and studied at the Institute of Field and Vegetable Crops in Novi Sad (Serbia) consisting of local autochthonous material as well as accessions from over the world representing a world collection of broomcorn (Berenji, 1990, 2000a; Sikora and Berenji, 2006, 2007, 2008a).

By 1967 JC Stephens and others recognized the limits of the germplasm available in the US, especially for improving inbreds and hybrids, and formulated the Sorghum Conversion Program to introduce new germplasm sources into the USA (Stephens et al, 1967). A backcrossing program was started to begin the process of conversion to photoperiod insensitive, short statured sorghums. All converted lines received four backcrosses to the original exotic variety. The exotic varieties were used as male parents until the third backcross when they were used as the female parent in order to recover the original cytoplasm in the converted line. The converted lines were non-sensitive to photoperiod, matured normally in the United States, and were short statured, generally 3 or 4-dwarf in height, but occasionally 2-dwarf in height. Approximately 1,500 germplasm sources have been entered into the program with a full 702 accessions being converted. From these converted and partially converted lines selections for drought tolerance, insect and disease resistance, and a broadening of the genetic base of the commercial hybrids developed in the US has taken place (Berenji et al, 2006).

Because of the diversity and availability of these sorgum germplasm resources steady improvement in sorghum breeding has been accomplished. Considerable opportunities remain for exploiting the world collections to improve sorghum production globally (Dahlberg et al, 2008).

Sorghum production

In 2009, 82% of the harvested area of sorghum was within Africa and Asia, where average yields were 904 and 1,096 kg ha^{-1}, respectively. The United States harvested 2.2 million ha, while Europe harvested 151,526 ha and produced 4,355 and 4,451 kg ha-1, respectively (Food and Agricultural Organization of the United Nations, 2011). As reported by Boyer (1987), the record yield for grain sorghum was 20.1 t ha^{-1}. Sweet sorghum and sudangrass tend to be extremely high yielding as well. Nebraska has averaged 23t ha^{-1} (United States Department of Agriculture National Agricultural Statistics Service, 2011) of forage yields over the last 10 years but yields of over 35 t ha^{-1} have been reported in the literature (Worker and Marble 1968). However, sorghum is not a 'miracle crop'. For maximum yield it too requires inputs such as moisture and nutrients. Yield losses in grain sorghum are attributed to unfavourable physiochemical environments, accounting for approximately 79 % of the yield reduction, that prevents it from obtaining record yields.

The abiotic stress tolerance of sorghum, especially the enhanced tolerance to drought and adaptation to marginal lands has been well documented (Berenji, 1993). Under the same stressed environment the adaptation and yield stability of sorghum is more enhanced than that of maize. The present as well as the future of European field crop production should not neglect this comparative advantage sorghum possesses. Europe should exploit sorghum as an alternative for more efficient and stable grain and biomass production in regions where water is limiting and heat stress is a problem for maize (Berenji et al, 2004). With the expected increase of temperatures and decrease of precipitation as the result of global climate change and their effect on production of high input crops such as maize, the wide adaptability of sorghum could help alleviate crop losses in areas affected by abiotic stresses.

Very few biotic stresses occur on sorghum in Europe, which could be considered favourable for its utilization in this part of the world. Europe does not face the same pest problems as countries such as the US, which have greenbug (*Schizaphi graminum*) problems and Australia, which has to deal with midge (*Contarinia sorghicola*); both of which can have serious economic impacts on the production of this crop. Until recently maize in Europe has been ranked among the crops with very few biotic stress problems; however, during the last decade the Western Corn Rootworm (*Diabrotica virgifera virgifera*), previously unknown in Europe, has become a considerable pest problem for maize producers. It was first detected in July 1992 in the locality of Surčin (Serbia) near the Belgrade international airport. The origin of this introduction remains unknown (Čamprag, 1995). The pest started to spread at a rather rapid pace in the Danube Basin. In addition, several identifications outside of the Danube basin have now been reported. In 2002, it was found for the first time in France near airports close to Paris. This pest is likely to survive and develop wherever maize is grown in Europe. Insecticide use is quite limited, although growers can manage the rootworm problem very successfully through crop rotation. As sorghum is not among the hosts for Western Corn Rootworm, grain sorghum is an excellent replacement for corn in infected areas. Furthermore, sorghum could successfully replace corn in feed rations in the diets of many of the animals that currently depend on corn in areas where Western Corn Rootworm is an issue. The newly developed transgenic corn may change this situation, but in the light of Europe's current position on transgenic plants, transgenic corn for Western Corn Rootworm control will certainly not be a solution in the short or medium term in Europe.

The disease situation with sorghum could also be considered favourable in Europe (Berenji, 2000b). Diseases like head smut (*Sporisorium reilianum*) or downy mildew (*Peronosclerospora sorghi*), which can cause significant losses to sorghum growers in other parts of the world, are almost unknown in Europe. Anthracnose (*Colletotrichum graminicola*) (Balaž et al, 1997), fusarium (*Fusarium spp*.) (Lević et al, 2006) and maize dwarf mosaic virus (Berenji et al, 1993; Bagi et al, 2002, 2004) have been observed in Europe but without significant economic losses. As large-scale production of sorghum in Europe develops, pest and disease problems could also develop, but in the meantime european sorghum farmers could benefit from the lack of these pests and diseases.

Utilization of sorghum

Grain sorghum is the most commonly cultivated agronomic type of sorghum worldwide. The dwarf stemmed (combine) types are suitable for mechanical harvesting of the grain. The grain is characterized by its high energy and feeding value. Sorghum grain is used primarily for livestock feed and stems and foliage for green chop, hay, silage, and pasture in the United States and Europe and more recently in the United States as a feedstock for the renewable fuels industry and into the gluten-free food market. In Africa and India, it is an important part of the diet in the form of unleavened bread, boiled porridge or gruel, and specialty foods such as popped grain and beer. Grain sorghum is becoming a potential field crop in Europe for cattle feed (Berenji and Dahlberg, 2004).

Sweet sorghums are tall, thick stemmed, have high dry matter yields and usually are produced for sugar production. In the United States, these sorghums are used to produce a sweet syrup, similar to molassasse. Sudangrass along with sorghum-su-

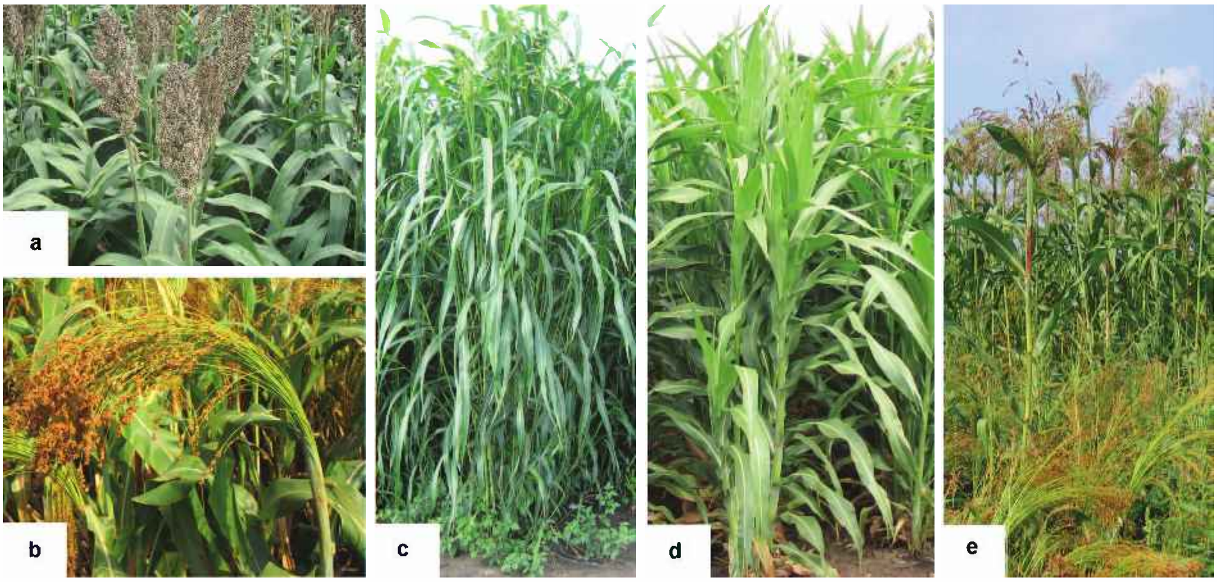

Figure 1 - Grain sorghum (a), broomcorn (b), sudangrass (c), sweet sorghum (d) and spontaneous sorghum (shattercane) in a broomcon field (e).

dangrass hybrids (hybrides of grain sorghum crossed with sudangrass) tend to be very leafy and grow rapidly and are best used for repeated cutting, animal grazing or baling for hay.

Broomcorn is a speciality sorghum recognizable by long panicles (heads) which are composed of long, fine, elastic branches called fibres with seeds on their tip used for manufacture of corn brooms (Berenji and Kišgeci, 1996). This widespread utilization of sorghum is based upon its diverse genetic background.

Human food

Traditionally, sorghum has been used in unfermented and fermented breads, porridges, couscous, rice-like products, snacks, and malted alcoholic and non-alcoholic beverages in the diets of many African and Asian countries. There have been attempts to introduce sorghum into the food market of the developed countries, but currently there are few food products available to consumers in Europe or in the USA even though several researchers have developed products from sorghum (Badi and Hoseney, 1976; Carson et al, 2000; Cauvain, 1998; Choto et al, 1985; Lindell and Walker, 1984; Morad et al, 1984; Satin, 1988; Serna-Saldivar et al, 1988; Suhendro et al, 2000; Young et al, 1990).

There are also several groups working on unique health properties associated with sorghum grain that could have an impact on its use in the health food industry. Ciacci et al (2007) reported on the in vitro and in vivo safety of sorghum food products and found that sorghum did not show toxicity for celiac patients and can be considered safe for use by those with celiac disease. Schober et al (2005) developed several gluten-free sorghum products and studied the effects of different sorghum hybrids on food characteristics. Groups such as Lloyd Rooney at Texas A&M University, Scott Bean, United States Department of Agriculture, Agricultural Research Service (USDA-ARS), Manhattan, Kansas, and Ron Prior, USDA-ARS, Little Rock, Arkansas are exploring the antioxidant activities of some unique sorghum cultivars and other such nutritional aspects of sorghum relevant to its use as human food. Tannin sorghums have very high levels of antioxidants with levels in the bran that are comparable to blueberries (Waniska, 2000; Awika and Rooney, 2004; Awika et al, 2003, 2004; Hagerman et al, 1998). There is growing evidence that some of these sorghums have high anti-inflammatory and anti-colon cancer activities. Special sorghums have been identified with very high levels of the rare 3-deoxy anthocyanins that have unique color stability and potential health applications (Dykes and Rooney, 2006).

Cattle feed

Grain sorghum has been successful used as cattle feed (Berenji and Kunc, 1995; Berenji and Mijavec, 1982; Mijavec and Berenji, 1982). Sweet sorghum and sudangrass in Europe is used for cattle feed, similar to the use of silage maize (Kunc et al, 1990). Proper cultivar choice and production technology will completely eliminate prussic acid (HCN) problems sometimes associated with fresh sweet sorghum or sudangrass used for feed (Kunc et al, 1995). Improvements in feed technology already common in the USA are highlighted by various feeding guides produced by the United Sorghum Checkoff Program (see http://www.sorghumcheckoff.com/feed) and could enhance the feed use of grain sorghum in Europe.

Industrial uses

Broomcorn is a classic example of industrial use of sorghum in Europe (Berenji and Sikora, 2002a, 2002b). After threshing and cutting off the peduncle, the remaining fibres serve as raw material for manufacturing of corn brooms. Europe, especially Serbia, Hungary, Romania and Bulgaria could be considered as the most significant world producers of broomcorn and corn brooms.Trends favouring ecological and natural products of all kinds have led to renewed interest in old-fashioned, biodegradable, wooden-handled brooms, which have had a positive impact on broomcorn production. The brooms are products of a well-organized niche market (Berenji et al, 2011).

Attempts have been made to develop the technology to utilize sorghum for paper production (usually utilizing robust F1 hybrids obtained by crosses with grain sorghums and broomcorn) (Petrini et al, 1993). This could provide an attractive replacement for present forest-derived raw material for the paper industry. In spite of several promising proposals (Rajki-Siklósi, 1996), little work has continued in this area.

Renewable energy

Sorghum is an excellent crop for production of renewable fuels (Berenji, 1994; Kišgeci et al, 1983). Sorghum is an excellent example of an annual crop that could be both a short term and long term solution as a renewable, sustainable biomass feedstock. Sorghum is unique among the crops being discussed as feedstocks for renewable energy in that it can be used in all the various processes being discussed and debated for biofuel production; starch-to-ethanol, sugar-to-ethanol, and cellulosic/lignocellulosic-to-biogas. The ethanol market is one of the fastest growing segments of the sorghum industry in USA representing the single-largest value-added market for grain sorghum producers in the USA. There are currently eight ethanol plants in USA that use about 15-20% of the USA grain sorghum crop each year. Equal quantities of ethanol are produced from the same amount of grain sorghum as from maize. Similar experimental results have been achieved in Europe (Kišgeci and Pekić, 1983). Research is underway to evaluate the use of sweet sorghum in processes similar to what is currently available in sugarcane for the production of ethanol. Recently, Dahlberg et al (2011) published research on compositional and agronomic evaluation of sorghum biomass. They reported that sorghum forages could produce high biomass yields over a wide number of years and that using theorectical estimates for ethanol productions these forages could average 6,146 L ha^{-1} of renewable fuels with a maximum production of 8,422 L ha^{-1} from the top ranged forage hybrids. These findings and sorghums diversity as a feedstock for renewable fuels production has potential for Europe as it attempts to formulate alternative energy production strategies.

Conclusions

Sorghum is an ancient, old world cereal that was domesticated in Africa and spread throughout the world to became one of the most important cereal crops known to man. Europe, at one time, knew the crop for grain production and broom manufacturing. For various reasons, European farmers moved away from sorghum and adopted other cropping system. Recently, there has been renewed interest in sorghum as a crop for European farmers. Some of this can be attributed to its non-GMO status, its drought tolerance, and its wide adaptability. Moreover, new uses for sorghum in food systems and renewable energy make it a promising “new” crop for European farmers looking to diversify their farming operations and meet the challenges of feeding and fueling the world.

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