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REVIEW ARTICLE

ORIGIN, DOMESTICATION, TAXONOMY, BOTANICAL DESCRIPTION, GENETICS AND CYTOGENETICS, GENETIC DIVERSITY AND BREEDING OF SORGHUM (*Sorghum bicolor* (L.) Moench)

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ABSTRACT

Sorghum belongs to the Family Poaceae, Subfamily Panicoideae, Supertribe Andropogonodae, Tribe Andropogoneae, Subtribe Saccharinae, Genus *Sorghum* and Species *Sorghum* bicolor (L.) Moench. Taxonomically it was first described by Linnaeus in 1753 under the name *Holcus*. Originally he delineated several species of *Holcus*, some of which have been later moved to the tribe Avenae, where the generic name *Holcus* now belongs. In 1794, Moench distinguished the genus *Sorghum* from genus *Holcus*. It is a grass species cultivated for its grain, which is used for food for humans, animal feed, and ethanol production. Sorghum is native to Ethiopia. Seventeen of the 25 species are native to Australia, with the range of some extending to Africa, Asia, Mesoamerica, and certain islands in the Indian and Pacific Oceans. All the cultivated sorghum taxa of the world have been classified by inflorescence type, grain and glumes into five races (Durra, Bicolor, Caudatum, Kaffir and Guinea) and intermediates involving all of the pair-wise combinations of the basic races. Sorghum is considered as an often cross-pollinated species, with out-crossing up to 6 % depending on the genotype and growing conditions. There are four main types of sorghum *viz,* Grain sorghum, Forage sorghum, Sweet sorghum and Biomass sorghum. Fruit is a caryopsis (grain) partially covered by glumes, round and bluntly pointed consists of embryo, endosperm and seed coat consists of pericarp and testa. Coleoptiles and roots emerge from the germinating seeds. Sorghum grain is used for human food and as feed for animals; the plant stem and foliage are used for green chop, hay, silage, and pasture. In some areas the stem is used as building material, and plant remains (after the head is harvested) may be used for fuel. It is a C_4 plant with higher photosynthetic efficiency and higher abiotic stress tolerance adapted to a range of environments around the world. Its small genome makes sorghum an attractive model for studying the functional genomics of C_4 grasses. Drought tolerance makes sorghum especially important in dry regions such as northeast Africa (its center of diversity), India, and the southern plains of the United States. Genetic variation for micronutrient concentration and its ability to absorb, translocate, and accumulate higher micronutrients in grain makes it an important model for biofortification research. Its high level of inbreeding makes it an attractive association genetics system. Sorghum is one of the cheapest sources of energy and micronutrients, and a vast majority of the population in sub-Saharan Africa and India depend on it for their dietary energy and micronutrient requirement. Sorghum provides more than 50 % of the dietary micronutrients, particularly Fe and Zn, to the low-income group, particularly in rural India where both physical and economic access to nutrient-rich foods is limited. Thus, sorghum is a unique crop with multiple uses as food, feed, fodder, fuel, and fiber. The crop improvement methods depend on the pollination control mechanisms and cultivar options. As mentioned earlier, sorghum is a breeder-friendly crop. One can employ the breeding methods that can be used to improve both self- and cross-pollinated crops with ease in sorghum. This is the reason why one can find sorghum pure line varieties, hybrids, and populations as cultivar options in different parts of the world. Nearly all grain sorghum is harvested as a standing crop with a combine. Combining time will depend on the fall weather and the availability of grain drying facilities. Sorghum grain can be threshed free of the head when the seed moisture is 20-25 percent. The seed is hysiologically mature at even higher moisture levels. The grain sorghum crop can be harvested for high-moisture grain silage. When fed to livestock, its digestibility will be increased by grinding or rolling. High moisture grain sorghum can be combined and ensiled when the grain is about 25-30% moisture. In the early stages of plant growth, some sorghum species may contain levels of hydrogen cyanide, hordenine, and nitrates lethal to grazing animals. Plants stressed by drought or heat can also contain toxic levels of cyanide and nitrates at later stages in growth. In this review article on Origin, Domestication, Taxonomy, Botanical Description, Genetics and Cytogenetics, Genetic Diversity, Breeding, Uses, Nutritional Value and Health Benefits of Sorghum are discussed.

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INTRODUCTION

Sorghum belongs to the Family Poaceae, Subfamily Panicoideae, Supertribe Andropogonodae, Tribe Andropogoneae, Subtribe Saccharinae, Genus *Sorghum* and Species *Sorghum bicolor* (L.) Moench (Inspection, 2021; Wikipedia, 2023). Taxonomically it was first described by Linnaeus in 1753 under the name *Holcus*. Originally he delineated several species of *Holcus*, some of which have been later moved to the tribe Avenae, where the generic name *Holcus* now belongs. In 1794, Moench distinguished the genus *Sorghum* from genus *Holcus* (Kumar, 2016). The word "sorghum" typically refers to cultivated sorghum (*Sorghum bicolor* [L.] Moench subsp. bicolor), a member of the grass family Poaceae, tribe Andropogoneae, and subtribe Sorghinae that is grown for its grain (grain sorghum), its sugary sap (sweet sorghum) or as a forage (forage sorghum) (OECD, 2017). It is a grass species cultivated for its grain, which is used for food for humans, animal feed, and ethanol production (Wikipedia, 2023). Seventeen of the 25 species are native to Australia, with the range of some extending to Africa, Asia, Mesoamerica, and certain islands in the Indian and Pacific Oceans (Wikipedia, 2023). All the cultivated sorghum taxa of the world have been classified by inflorescence type, grain and glumes into five races (durra, bicolor, caudatum, kaffir and guinea) and intermediates involving all of the pair-wise combinations of the basic races (de Wet, 1978; Harlan and de Wet, 1972). *Sorghum bicolor* is commonly known in English as broomcorn, chicken-corn, common wild sorghum, durra, feterita, imphee, jowar, forage sorghum, grain sorghum, sweet sorghum, great millet, milo, Guinea corn, Indian millet, cholam, jonna, kafir corn, kaoliang, mtama, sweet sorghum, Rhodesian Sudan grass, shallu, shattercane, sordan, sorghum, sorghum-Sudan grass, and Sudan grass. French common names include gros mil, sorgho du Soudan, sorgho menu, and sorgho (Inspection, 2021; Wikipedia, 2023; Britannica, 2023). Local names in different languages are as follows: Swahili: mtama; Spanish: sorgo; French: sorgho; German: sorghum; Italian: sorgo; Portuguese: sorgo; Chinese (Mandarin) gāo liáng; Japanese: morokoshi; Hindi: jwar); Arabic: al-dhurrah al-sawda (Plantvillage, 2023). Sorghum is considered as an often cross-pollinated species, with outcrossing up to 6 % depending on the genotype and growing conditions (Hariprasanna and Patil, 2015). There are four main types of sorghum *viz.*, Grain sorghum, Forage sorghum, Sweet sorghum and Biomass sorghum (Venkateswaran *et al.*, 2019). The four major types of sorghum are as follows:

Grain Sorghum: Grain sorghum can take many shapes and sizes from a tight-headed, round panicle to an open, droopy panicle that can be short or tall. Grain sorghum comes in red, orange, bronze, tan, white, and black varieties. Red, orange or bronze sorghum are very versatile and can be used in all segments of the sorghum industry. Tan, cream and white colored sorghum varieties are typically made into flour for the food industry. Black and burgundy varieties contain beneficial antioxidant properties and are used in other food applications.

Forage Sorghum: Depending on which species and variety is selected, sorghum can be used for grazing pasture, hay production, silage and green-chop. Forage sorghum typically grows 8-15 feet tall and is most popular for use as silage for feeding livestock.

Biomass Sorghum: Did you know sorghum can be used to make ethanol? Biomass sorghum has the largest stature of all the sorghum varieties, reaching a height of 20 feet in a normal growing season. Biomass sorghum has been bred to produce a large amount of non-grain biomass. These hybrids are used primarily for the production of bioenergy.

Sweet Sorghum: Sweet sorghum is predominantly grown for sorghum syrup. Unlike grain sorghum, sweet sorghum is harvested for the stalks rather than the grain and is crushed like sugarcane or beets to produce a syrup. Sweet sorghum was once the predominate table sweetener in the U.S. Today, sweet sorghum is used as a healthy alternative sweetener to produce whiskey and rum type products and for biofuel and chemical production.

In India, the rainy-season sorghum grain is used mainly as animal/poultry feed, while the post-rainy-season sorghum grain is used primarily for human consumption (Reddy, 2017). Sorghum is a tropical grass that is grown primarily for its grain, although sweet sorghum (sorgo) is grown for the sugar-rich juice in its stem, and broomcorn is grown for its branches. Sorghum produces small, round grains that are often white or red in color. The scientific naming of wild and domesticated sorghum species is complicated, although the domesticated forms are now usually placed in *Sorghum bicolor* subspecies *bicolour (*Evolution, 2023*)*. Sorghum, a C4 grass that diverged from maize around 15 million years ago, is the fifth most important cereal grown worldwide. Sorghum is well adapted to tropical and subtropical climates, but the greater part of the area of the crop falls in drought-prone, semi-arid tropical regions of the world. In these harsh environmental conditions sorghum is predominantly grown for human consumption followed by animal feed and fodder. Sorghum could also play an important role in its alternate uses in brewing industry for the production of ethanol, starch and syrup (Balakrishna and Bhat, 2016). -Cultivated sorghum ranks fifth in worldwide cereal crop production behind maize, rice, wheat and barley. It is a widely adapted species capable of growing in semiarid, subtropical, tropical and temperate climates. An extensive root system and the ability to become dormant during water stress make cultivated sorghum drought-resistant, typically requiring only one-half to two-thirds the amount of rainfall as maize (OECD, 2017). Sorghum, a cultivated diploid (2n = 20) tropical cereal C4 grass plant, is the fifth most important cereal crop grown in the world. It is a monocotyledon plant of tropical origin (Nagara, 2017). Sorghum is called as camel of crops due to the high tolerance of water and temperature stress and also high photosynthesis efficiency; it is considered as an important plant in arid and semi-arid regions (Anagholi *et al.*, 2000).

Admas and Tesfaye (2018) described that sorghum is native to Ethiopia and it has remarkable genetic diversity as evidenced by many landrace collections made in the country. It is well adapted to a wide range of environmental conditions in semi-arid Africa. The largest diversity of the crop germplasm provides greater opportunities for improvement regarding its environmental adaptability and acquiring better agronomic traits fom the crop species. Identifying and selecting the best varieties meeting specific local food and industrial requirements from this great biodiversity is of high importance for the food security assurance of any given country (Dahlberg *et al.*, 2002). Sorghums are of tropical origin, but have spread all over the world, with current production in many countries including Africa, China, Central and South America, India, and the United States (USDA, 2023).

Genetic variability is prerequisite in the existing population for varietal improvement. Loss of genetic variability leading to genetic erosion has led to greater emphasis on germplasm collection and characterization for present and future plant breeding programmes (Prasanna, 2010). Knowledge of genetic diversity of a crop usually helps the breeder in choosing desirable parents for the breeding program and gene introgression fom distantly related germplasm. The more diverse genotypes or accessions can be crossed to produce superior hybrids with resistance to abiotic and biotic stresses. Understanding the wealth of genetic diversity in sorghum will facilitate the further improvement of this crop for its genetic architecture (Elangovan and Babu, 2015). It is a C_4 plant with higher photosynthetic efficiency and higher abiotic stress tolerance adapted to a range of environments around the world. Its small genome makes sorghum an attractive model for studying the functional genomics of C_4 grasses.

Drought tolerance makes sorghum especially important in dry regions such as northeast Africa (its center of diversity), India, and the southern plains of the United States. Genetic variation for micronutrient concentration and its ability to absorb, translocate, and accumulate higher micronutrients in grain makes it an important model for biofortification research. Its high level of inbreeding makes it an attractive association genetics system (Kumar, 2016). Sorghum is a staple food crop for millions of poor people in the semiarid tropics of Africa and Asia. It is one of the important dryland crops grown in marginal soils and a source of feed, fodder and biofuel apart from food. It is a short-day C_4 plant, and its easy adaptability to hot and dry agroecologies makes it a climate change-compliant crop (Hariprasanna and Patil, 2015). Sorghum is the fifth most important cereal crop after wheat, rice, maize, and barley across the world. It is mostly cultivated in the arid and semi-arid tropics for its better adaptation to drought, heat, salinity, and flooding. It is the main staple food for the poorest and most food-insecure people of the world (Prabhakar *et al.*, 2022). Fruit is a caryopsis (grain) partially covered by glumes, round and bluntly pointed consists of embryo; endosperm and seed coat consists of pericarp and testa. Coleoptiles and roots emerge fom the germinating seeds (Balakrishna and Bhat, 2016).

Sorghum grain is used for human food and as feed for animals; the plant stem and foliage are used for green chop, hay, silage, and pasture. In some areas the stem is used as building material, and plant remains (after the head is harvested) may be used for fuel (House, 1985). Sorghum is one of the cheapest sources of energy and micronutrients, and a vast majority of the population in sub-Saharan Africa and India depend on it for their dietary energy and micronutrient requirement. Sorghum provides more than 50 % of the dietary micronutrients, particularly Fe and Zn, to the low-income group, particularly in rural India where both physical and economic access to nutrient-rich foods is limited. Thus, sorghum is a unique crop with multiple uses as food, feed, fodder, fuel, and fiber (Kumar, 2016). The major organisations/countries which maintain sorghum genetic resources are the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India, the National Plant Germplasm System (NPGS) in United States, Ethiopia, Sudan, South Africa, India and China, primarily because of the large crop improvement programmes (Reddy, 2017). The crop improvement methods depend on the pollination control mechanisms and cultivar options. As mentioned earlier, sorghum is a breeder-fiendly crop. One can employ the breeding methods that can be used to improve both self- and cross-pollinated crops with ease in sorghum. This is the reason why one can find sorghum pure line varieties, hybrids, and populations as cultivar options in different parts of the world. However, sorghum hybrids are superior to pure lines and populations for yield and other important agronomic traits. The discovery of cytoplasmic-nuclear male sterility in sorghum helped to produce hybrid seeds on a mass scale using a three-line system (A, B, and R) for commercial cultivation of hybrids (Kumar, 2016). Trait-based approach for the genetic improvement of sorghum has been adopted by use of cutting-edge technologies of plant biotechnology and molecular biology to develop genotypes with improved performance under stress during crop growth and enhanced quality of the produce with extended shelf life of seed, grain, and novel sorghum products (Prabhakar *et al.*, 2022).

Nearly all grain sorghum is harvested as a standing crop with a combine. Combining time will depend on the fall weather and the availability of grain drying facilities. Sorghum grain can be threshed fee of the head when the seed moisture is 20-25 percent. The seed is physiologically mature at even higher moisture levels. Frost will generally kill the top of the plant and help to lower the moisture content. Some hybrids have a loose, open type head which hastens field drying. The grain sorghum crop can be harvested for high-moisture grain silage. When fed to livestock, its digestibility will be increased by grinding or rolling. High moisture grain sorghum can be combined and ensiled when the grain is about 25-30% moisture (Carter *et al.*, 2023). Harvest is done mostly by hand in developing countries. The panicle containing the grains are cut from the stalk when appropriate moisture content of 16-20 % is reached. Seed maturity can be recognized by the appearance of a black spot at the connection between seed and plant. Threshing can then be done either manually or mechanically. Before storing the seeds, they need to reach a moisture content of only 10%, as higher moisture content contributes to the growth of mould as well as to the germination of the seeds (Wikipedia, 2023). Sorghum is marketed according to US grain standards in four classes: sorghum, white sorghum, tannin sorghum, and mixed sorghum. The sorghum class cannot contain more than 3 % sorghum with a pigmented testa (undercoat). Tannin sorghums have a pigmented testa beneath the pericarp. The pigmented testa is seen as a dark layer between the light endosperm and the pericarp when the caryopsis is scraped to remove the pericarp. Bleaching using the chlorox bleach test causes the constituents in the pericarp and testa to oxidize and gives a pronounced black color to the bleached kernels while nontannin sorghums have a white appearance. The white class contains sorghum with a white pericarp without a pigmented testa and cannot contain more than 2% of sorghum with pigmented testa or colored pericarp. Mixed sorghum contains a blend of kernels with and without pigmented testa. The US also markets “Food-Grade” white sorghum, a white kernel with tan plant and glume characteristics. The amounts of anthocyanin pigments that darken these grains are less than those from grain with purple or red glumes (Waniska *et al.*, 2004).

Sorghum is classified in North America according to its use as a grain sorghum, sweet sorghum, grass sorghum, broomcorn, or special purpose. The statistics presented in this article for sorghum refer only to the grain sorghums. Sorghum is used in North America primarily as an animal feed. Small quantities are also used for food manufacture (flour) and still smaller quantities of sorghum are used for food (breads, grits, breakfast cereals), other uses (starch), and planting seed (Lukow and McVetty, 2004). The pollen grains germinate immediately after contact with receptive stigma. It is reported that sorghum pollen requires light and germinates only after daybreak. The pollen tubes grow through the stigmatic papiuae down the ovary, through style. Fertilization between egg-cell and sperm takes place within two hours and develops into an embryo (2n). Second fertilization occurs between polar nuclei and sperm and develops into an endosperm (3n). The seed development reaches physiological maturity with 30 to 40 days after fertilization. The ripe seed (grain) of sorghum is usually partially enclosed by glumes, which are removed during threshing and/or harvesting. The shape of the seed is oval to round and the color may be red, white, yellow, brown, or shades thereof. If only the pericarp is colored, the seed is usually yellow or red. Pigment in both the pericarp and testa are in a dark-brown or red-brown color. The sorghum grain consists of the testa, embryo, and endosperm The seed coat consists of the pericarp and testa. Pericarp is the outermost layer of the seed and consists of the epicarp, hypodermis, mesocarp, and endocarp. The testa is situated directly below the endocarp and encloses the endosperm. The seeds of sorghum species can be spread via wind, water, animals, or humans (clothing, harvest machinery, vehicles) and can travel to long distance when carried by birds or livestock (Balakrishna and Bhat, 2016).

The sorghum crop should be harvested immediately after grain maturity. The right time for harvest is when grains become hard and contain less than 25% moisture. Generally 2 methods of harvesting *i.e.*, stalk cut and cutting of earheads by sickles are adopted. However, in advanced countries, sorghum harvesters are used. In case of stalk cut method, the plants are cut from near the ground level. The stalks are tied into bundles of convenient sizes and stacked on the threshing floor. After 2-3 days, the earheads are removed from the plants. In other method, earheads only are removed from the standing crop and collected at the threshing floor for threshing after 3-4 days of sun-drying. Threshing of earheads is done either by beating them with sticks or by trampling under bullock feet. Threshing is also done with the help of threshers. The threshed grain should be cleaned and dried in sun for 6-7 days to reduce the moisture content down to 13-15% for safe storage (Balakrishna and Bhat, 2016). Sorghum seed is easily damaged in the threshing operation, especially when the grain is dry. The combine platform should be operated as high as possible to minimize the mass of stems entering the combine. If necessary, the cylinder speed can be reduced to one-half that used for wheat to prevent cracking the seed. However, grain moisture will normally be higher and faster cylinder speeds can be used. The recommended cylinder speed is 750 -1300 R.P.M. but loss determinations should be made to refine the combine adjustments. An average loss of 19-22 kernels per square foot is equal to one bushel per acre loss (Carter *et al*., 2023).

Grain sorghum can be dried with corn drying equipment. However, because the grain is smaller in size, fans may need to be operated at higher static pressure than used for corn. Also, grain sorghum needs to be somewhat drier than corn for safe storage since there is less air movement through the grain. Grain should be stored at 13% moisture and in clean bins. The grain should not be heated over 200° F since feeding values are reduced by high temperature (Carter *et al*., 2023). In the early stages of plant growth, some sorghum species may contain levels of hydrogen cyanide, hordenine, and nitrates lethal to grazing animals. Plants stressed by drought or heat can also contain toxic levels of cyanide and nitrates at later stages in growth (Wikipedia, 2023)

The global area under sorghum cultivation is estimated at 42.12 million hectares, and the production of sorghum has been estimated to be at the level of 61.38 million tonnes. India stands second globally for the area under sorghum cultivation (6.18 million hectares) and its production (5.28 million tonnes) (Balakrishna and Bhat, 2016). Sorghum is among the top 10 crops that feed the world. It is the dietary staple of more than 500 million people in over 30 countries, primarily in the developing world. It is grown on 40 m ha in more than 90 countries in Africa, Asia, Oceania, and the Americas. The top 10 sorghum producers globally are the United States, India, Mexico, Nigeria, Sudan, Ethiopia, Australia, Brazil, China, and Burkina Faso. Sorghum accounts for 6 % of the global coarse cereals production in the world and is particularly well suited to hot and dry agroecologies in the world. Global sorghum productivity is low (1.4 t ha^{-1}) with wide variation in different parts of the world. Although productivity is high in the Americas, China, and Australia, it is low in India, Nigeria, and Sudan (Kumar, 2016). Broadly, the world sorghum economy consists of two distinct production systems: a traditional, subsistence, smallholder farming production system where most of the production is consumed directly as food (mainly in Africa and Asia) with limited or no marketable surplus, and a modern, mechanized, high-input, large-scale sector where output is used largely as animal feed (mainly in the developed countries and in Latin America). The future of the sorghum economy is linked with its contribution to food security in Africa, income growth and poverty alleviation in Asia, and the efficient use of water in drought-prone regions in much of the developed world (Kumar, 2016). *Sorghum bicolar* (2n-2x-20) comes fifth after wheat, maize, rice, and barley in both area and production. It is one of the most important food crop in the semi and tropics of India, Africa. Australia, Argentina, mexico. In India it is cultivated on large scale in Maharashtra, Gujrat, Tamil Nadu, Karnataka, Rajasthan and M.P. (Agri info, 2016).

Sorghum is the fifth most important cereal crop in the world next to maize, rice, wheat, and barley in terms of both production and harvested area. It is a major food crop for more than 500 million people across Afica, Asia, and Latin America, particularly for those in the semi-arid tropical regions. It is grown in drought-prone areas where several other crops cannot reliably grow. Sorghum covered about 40 million ha of land and produced grains of ca 57.9 million metric tons (MMT). The United States, Nigeria, and Ethiopia are the leading sorghum-producing countries in the world with a total production of 8.6, 6.7, and 5.2 MMT, respectively. In Africa, sorghum is the second most widely cultivated cereal crop, only surpassed by maize (Enyew *et al.,* 2021). Sorghum can be grown in large parts of the temperate zone because it is an annual crop that does not require an extremely long growing season. Today, sorghum is the world's number five **cereal** (grass grain) crop, after maize, wheat, rice, and barley. The top producers of sorghum are the United States and Nigeria, followed by Ethiopia, India, Mexico, and China *(*Evolution, 2023*)*. In 2021, world production of sorghum was 61 million tonnes, led by the United States with 19% of the total. India, Ethiopia, and Mexico were secondary producers **(Fig.1)** (Wikipedia, 2023). In this review article on Origin, Domestication, Taxonomy, Botanical Description, Genetics and Cytogenetics, Genetic Diversity, Breeding, Uses, Nutritional Value and Health Benefits of Sorghum are discussed.

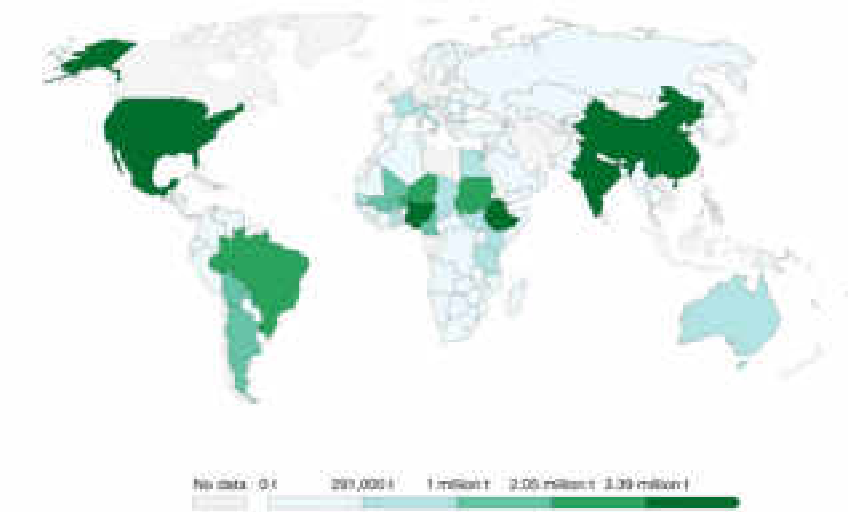

Fig. 1: World map of sorghum production in 2020 by country

ORIGIN AND DOMETICATION

Ethiopia is the Vavilovian centers origin/diversity for sorghum (Vavilov, 1951). Sorghum originated in Africa, more known in Ethiopia, between 5000 and 7000 years ago (ICRISAT, 2005). Currently sorghum is widely found in the dry lowland areas of Africa, Asia (India and China), the Americas and Australia. It is an economically, socially and culturally important crop grown over a wide range of ecological habitats in Ethiopia, in the range of 400-3000 m.a.s.l (Teshome *et al,* 2007). Then, it was distributed along the trade and shipping routes around the African continent, and through the Middle East to India at least 3000 years ago. It then journeyed along the Silk Route into China. It was first taken to North America in the 1700-1800's through the slave trade from West Africa and was re-introduced in Africa in the late 19th century for commercial cultivation and spread to South America and Australia (Yitayeh, 2019).

The origin and early domestication of sorghum took place in Northeastern Africa, north of the Equator and east of 10º E latitude approximately 5000 years ago. New evidence, however, may place the origin at 8000 years before present (BP), 3000 years earlier than previously thought and 10-15 º latitude further north than had been reported earlier, since carbonized seeds of sorghum, with consistent radiocarbon dates of 8000 years BP, were excavated at an early Holocene archaeological site E-75-6, at Nabta Playa, near the Egyptian-Sudanese border. Early domestication of sorghum occurred from Ethiopian borders extending west through Sudan and up to Lake Chad. There is great prevalence of diversity in this area as apart from the presence of the primitive race bicolor (Harlan and de Wet, 1972). It is likely that this race arose from the domestication of *Ethiopicum verticilliflorum* complex some 3000 to 5000 years ago. The finding at Nabta Playa may cause some rethinking of dates; however, it is not clear if these 8000 year old seeds were from plants that did not shatter grains, although altered chemical composition would indicate some selection. *Bicolor* sorghum has spread across much of the old sorghum growing world including India. It is the likely progenitor of the kaoliongs of China (Mann *et al.,* 1983).

The race guinea arose from *bicolor* with possible interaction with the wild race *arundinaceum* in the high rainfall areas of West Africa. The guinea is now the dominant sorghum of West Africa but has spread also around Tanzania and Malawi. The guinea race arose more than 2000 years ago. The race *caudatum* also possibly evolved from *bicolor*. Today, the *caudatums* are most abundant from east Nigeria to eastern Sudan and southward into Uganda. The race durra was selected from early *bicolor* that had moved into India some 3000 years ago. With Arab migration the durra moved into Ethiopia around 615 A.D and is today the dominant race in India, Ethiopia, the Nile Valley of Sudan, and Egypt. Race *kafir* was probably derived from *bicolor* but there is also evidence of association with the wild race verticilliflorum. The *kafir* is found primarily in eastern and southern Africa (Mann *et al.,* 1983). Later sorghum found its way into the Americas after 1850. Africa has largest diversity of cultivated and wild sorghum. In Indian subcontinent, evidence for early cereal cultivation was discovered at an archaeological site in western parts of Rojdi (Saurashtra) dates back to about 4500 before present (Damania, 1980) and considered to be secondary center of origin of sorghum. Vavilov (1951) indicated that Ethiopia was a center of diversity; and the center of origin of sorghum. Harlan (1971) expanded on Vavilov's work and proposed that agriculture originated independently in three different areas and that, in each case, there was a center of origin and several non-centers in which activities of domestication were dispersed over a spatial span of 5000 to 10000 kilo meters. Southern Eurasia, east to India is the native of *Sorghum halepense*, a perennial plant with well developed, creeping rhizomes, and has been introduced as a weed to all warm temperate areas of the world (de Wet, 1978). *Sorghum propinquum* is another perennial with stout rhizomes and occurs primarily in Sri Lanka and Southern India. It is also found between Burma eastward to the islands of Southeastern Asia. *S. bicolor* has two wild subspecies associated with it, *S. bicolor* subsp. *drummondii* and *S. bicolor* subsp. *verticilliflorum*. Subspecies *drummondii* is an annual weed associated with both cultivated sorghums and their wild relatives. Subspecies *drummondii* occurs primarily in Africa and hybridizes with subspecies *bicolor*; all wild relatives to produce shattercane type weeds (Balakrishna and Bhat, 2016). Sorghum originated in Ethopia and South Asia. The progenitor of *S. bicolar* is *Sorghum arundinaceum* (2n=20) (Agriinfo, 2016). Sorghum is a tropical grain grown primarily in semi-arid parts of the world. In Africa, a major growing area runs across West Africa south of the Sahara, through Sudan, Ethiopia, and Somalia. It is grown in Egypt and Uganda, Kenya, Tanzania, Burundi, and Zambia. It is an important crop in India, Pakistan, Thailand in central and northern China, Australia, in the drier areas of Argentina and Brazil, Venezuela, USA, France and Italy. Globally, Sorghum is cultivated in an area of 42-43 million hectares to produce 59-60 million tonnes (Balakrishna and Bhat, 2016).

Centre of domestication and ancient geographic distribution: Sorghum's centre of domestication is likely the Ethiopia-Sudan region in North-east Africa because the greatest plant diversity and variation in ecological habitats occurs there. Archaeological evidence suggests sorghum was originally cultivated around 5000 B.P. Studies comparing the morphology of ancient and modern grain and data from molecular markers agree that the different races be classified as the same biological species. It is possible that a single domestication event occurred and that the various races were derived from it. Alternatively, multiple domestication events may have occurred, leading to the development of different races that subsequently anastomosed into the current, extant *S. bicolor* lineage (OECD, 2017). Cultivated sorghum was transported from Africa to India via trade routes over the Arabian Peninsula and the Indian Ocean. Durra varieties began emerging in India as the crop was adapted to the environmental conditions and needs of people. The earliest archaeological evidence of domesticated sorghum in India is dated around 4000 B.P. Domesticated sorghum continued to be spread from India to the People's Republic of China along overland trade routes. In China, the crop was adapted to tolerate temperate conditions and varieties known as the kaoliangs were developed that are tolerant of cooler early season temperatures. Sorghum came from Africa to America relatively recently through the slave trade. In the United States, the crop has been bred for commercial purposes since its introduction, resulting in the development of dwarf hybrids which are easier to cultivate on a commercial scale (OECD, 2017). Sorghum's adaptability to a range of environmental conditions allows it to be cultivated in multiple regions around the world with substantially varied climates. There are currently two main belts of cultivation in Africa. The northern belt ranges from the Ivory Coast north to the Sahara, and east towards Sudan and Ethiopia. The races *bicolor, durra, guinea* and *caudatum* are primarily grown in this belt. The second African sorghum belt runs north to south from Ethiopia to South Africa. Races grown include *kafir, bicolor* and *caudatum*. In India, sorghum is mainly cultivated on the Deccan Plateau, with only minor production in northern India. Sorghum is produced throughout China but the core of production is in the northern region, especially the areas north of the Qinling mountains, and between the Yellow and Yangtze Rivers (House, 1985; OECD, 2017).

Sorghum is an ancient crop of African origin and especially important in the semiarid tropics of Africa and South Asia, with significant production also in China, Southeast Asia, and the Americas. Questions regarding the time and place of its origin and domestication have been long deliberated on and debated. The earliest evidence of wild sorghums comes from hunter-gatherers in the Sahara dating to about 8000 BC, but the earliest known domesticated sorghum until now dated to 2000–1700 BC was reported from Late Harappan India where it is not a native crop. Recent archeo-botanical evidence, however, points toward the Eastern Sudanese savannah as a center of origin of sorghum cultivation (Venkateswaran *et al.,* 2019).

S. bicolor originated in Northeastern Africa, where large variability in wild and cultivated forms remains. Archaeological evidence from near the Egyptian-Sundanese border supports that *S. bicolor* was first cultivated 8,500 to 4,000 years B.P. during the early Holocene period. *S. bicolor* cultivation likely spread from Ethiopia, where it is believed domestication occurred, to Africa, the Middle East, and India along trade and shipping routes over 3,000 years ago. Cultivation then spread from India to China along the silk route, and to southeast Asia with seed moving through coastal shipping routes. *S. bicolor* was introduced into the United States (U.S.) for commercial cultivation from North Africa, South Africa, and India through the slave-trade at the end of the 19th century. *S. bicolor* cultivation in South America and Australia became substantial beginning around 1950. Currently, *S. bicolor* is widely cultivated in dry areas of Africa, Asia, the Americas, Europe, and Australia. Sorghum is cultivated between the latitudes of 50°N in North America and Russia and 40°S in Argentina (Vavilov, 1951; Harlan and De Wet, 1972; Inspection, 2021). There is little information on the cultivation of *S. bicolor* in Canada because production is minimal. Canadian field trials were conducted in the 1970s and 1980s assessing the suitability of domesticated sorghum as a crop. Interest in *S. bicolor* for forage, grain production, and use for bioenergy has increased in the past decade, especially in Southwestern Ontario and Quebec. Approximately 5,000 to 8,000 acres of *S. bicolor* are grown annually in eastern Canada and production and demonstration plots have also been planted in western Canada. On marginal land in eastern Ontario, forage sorghum hybrid CFSH-30 was grown at 1.1 million plants per hectare and yielded 14.5 Mg/ha/year (megagrams/ha/year) in one study and 1.6 to 4.8 Mg/ha/year in another study where crop establishment was poor. For ethanol crops, a study with three sweet sorghum varieties and four planting densities showed a production potential of up to 16 Mg/ha (with cv. 'Bulldozer') and sugar content as high as 22 Brix (with cv. 'Sugargraze'). Yields can range considerably among sites and years (Inspection, 2021). Ethiopia is the center of origin for sorghum where the distinct agro-ecological zones significantly contributed to the genetic diversity of the crops. A large number of sorghum landrace accessions have been conserved *ex situ*. Molecular characterization of this diverse germplasm can contribute to its efficient conservation and utilization in the breeding programs (Enyew *et al*., 2021). Sorghums are of tropical origin, but have spread all over the world, with current production in many countries including Africa, China, Central and South America, India, and the United States (USDA, 2023). Originating in Africa and subsequently spreading to different continents, sorghum has experienced multiple onsets of domestication and intensive breeding selection for various end uses (Wu *et al.,* 2022). Sorghum was domesticated from its wild ancestor more than 5,000 years ago in what is today Sudan. The newest evidence comes from an archaeological site near Kassala in Eastern Sudan, dating from 3500 to 3000 BC, and is associated with the Neolithic Butana Group culture. It was the staple food of the kingdom of Alodia (Wikipedia, 2023). Sorghum characterised by a tremendous amount of morphological variability is leading to dispute even in the area of greatest diversity. Vavilov placed its origin in the northeast Africa. There is evidence of sorghum in Assyria by 700 BC and in India and Europe by first AD. Domestication of sorghum is believed to have commenced in the area comprising Ethiopia and Egypt around 3000 BC. It is often accepted that the races of *durra, guinea* and *caffra* were derived from *S.aethiopicum, S.arundinaceum* and *S.verticilliflorum* respectively, as progenitors. Caffra is common in southern central (Bantu) Africa, *caudatums* in central Sudan and *guinea* in West Africa (Pallavi, 2023). Sorghum probably moved out of Africa to India and China through sailing ships. Evidence suggests that sorghum was established in India before the time of Christ but not earlier than 1500 BC. Cultivated sorghums were first introduced to America and Australia about 100 years ago. Sorghum was introduced into the Middle East and Mediterranean areas from Ethiopia and Egypt. The major sorghum producing areas today include the Great Plains of North America, Sub-Saharan Africa, Northeastern China, Deccan Plateau of India, Argentina, Nigeria, Egypt and Mexico. The USSR, France and Spain are the leading sorghum producing countries in Europe (Pallavi, 2023).

Sorghum originated in Africa, and is now cultivated widely in tropical and subtropical regions (Wikipedia, 2023). The plant likely originated in Africa, where it is a major food crop, and has numerous varieties, including grain sorghums, used for food; grass sorghums, grown for hay and fodder; and broomcorn, used in making brooms and brushes (Britannica, 2023). Scientists think that sorghum was domesticated from a wild form of sorghum more than 5000 years ago in the region of present-day Sudan. Cultivation of sorghum later spread to other regions, including India, other parts of Africa, East Asia, and the Mediterranean region, before sorghum was brought to the Americas *(*Evolution, 2023*).*

The first archaeological remnants of sorghum are at Nabta Playa on the Upper Nile, c. 8000 BC. However, these are wild sorghum, with small grains and a brittle rachis. Sorghum was domesticated from its wild ancestor more than 5,000 years ago in what is today Sudan. The newest evidence comes from an archaeological site near Kassala in eastern Sudan, dating from 3500 to 3000 BC, and is associated with the neolithic Butana Group culture. It was the staple food of the kingdom of Alodia. And most Sub-Saharan cultures prior to European colonialism. Sorghum grain cannot be consumed unless the indigestible husk is removed. During the transatlantic slave trade, "the only way to remove the husk was by hand, with mortar and pestle." In the United States enslaved women did most of the work in preparing the sorghum and were tasked with cleaning the grain and turning it into flour. Sorghum in the United States was first recorded by Ben Franklin in 1757. Some varieties of sorghum were important to the sugar trade. In 1857 James F.C. Hyde wrote, "Few subjects are of greater importance to us, as a people, than the producing of sugar; for no country in the world consumes so much as the United States, in proportion to its population." The price of sugar was rising because of decreased production in the British West Indies and more demand for confectionery and fruit preserves, and the United States was actively searching for a sugar plant that could be produced in northern states. The "Chinese sugar-cane" as it was called was viewed as a plant that would be productive and high-yielding in that region. In 19th-century Ethiopia, *durra* was "often the first crop sown on newly cultivated land", explaining that this cereal did not require the thorough ploughing other crops did, and its roots not only decomposed into a good fertilizer, but they also helped to break up the soil while not exhausting the subsoil. In 19th-century European accounts, many would use the term "millet" to refer to both pearl millet and sorghum (Wikipedia, 2023).

TAXONOMY

Sorghum was first described by Linnaeus (1753) under the name Holcus. Adanson used the name *Sorghum* as an alternative for *Holcus*. Moench later separated the genus Sorghum from genus *Holcus* (Clayton, 1961). Originally he delineated several species of *Holcus*, some of which have been later moved to the tribe Avenae, where the generic name *Holcus* now belongs. In 1794, Moench distinguished the genus *Sorghum* from genus *Holcus* (Kumar, 2016). Sorghum is classified under the family Poaceae, tribe Andropogoneae, subtribe Sorghinae, genus *Sorghum* Moench and Species *Sorghum bicolor* (L.) Moench. . Some authors further divided the genus into five subgenera *sorghum*, *chaetosorghum*, *heterosorghum*, *parasorghum*, and *stiposorghum*. Variation within these five subgenera except the subgenera *sorghum* has been described. *Sorghum bicolor* subspp. *bicolor* contains all of the cultivated sorghums (Kumar, 2016). Sorghum has been variously classified. In 1737 Linnaeus described two species of sorghum, one as *Holcus glumis glabris* and the other as *Holous glumis villosis*. Snowden (1936,1955) described 31 cultivated species and 17 related wild species. Snowden recognized that the cultivated sorghums could be considered races of one vast species, but he gave species status to the 48 different types to stress the fact that they are well defined by a number of distinct characters. At present his species are more appropriately considered to be races of one species. Snowden (1936) later subdivided the sorghums into the following sections, subsections, and series, leaving *Sorghastrum* as a separate genus to contain more distinct types. Celarier (1959) and De Wet (1978) gave the following five sections of Sorghum: *Stiposorghum, Parasorghum, Eusorghum, Heterosorghum, Chaetosorghum*. *Sorghum* comprises approximately 25 species, and is divided into five subgenera: *Chaetosorghum*, *Heterosorghum*, *Parasorghum*, *Stiposorghum*, and *Eusorghum*. In addition to *S. bicolor*, the subgenus *Eusorghum* contains the agronomically-important species *Sorghum propinquum* (Kunth) Hitchc. and *Sorghum halepense* L. (Pers.) (derived from past hybridizations between *S. bicolor* and *S. propinquum* (Inspection, 2021).

Currently, *S. bicolor* has three recognized subspecies: subsp. *bicolor*, subsp. *verticilliflorum* (Steud.) de Wet ex Wiersema & J.Dahlb, and subsp. *drummondii* (Steud.) de Wet ex Davidse. The subspecies *bicolor* includes the domesticated sorghum used for grain. It is divided based on floral morphology into five interfertile races (*bicolor, kafir, caudatum, durra*, and *guinea*) that can produce 10 intermediate races. Wild types of *S. bicolor* are included in the subspecies *verticilliflorum*. Annual weedy derivatives arising from the hybridization of domesticated sorghum and subspecies *verticilliflorum* make up the subspecies *drummondii*. The intergrades of the subspecies *drummondii* are highly variable due to gene segregation and include shattercane (a feral form) and Sudan grass (Inspection, 2021).

The word "sorghum" typically refers to cultivated sorghum (*Sorghum bicolor* [L.] Moench subsp. *bicolor*), a member of the grass family Poaceae, tribe Andropogoneae, and subtribe Sorghinae that is grown for its grain (grain sorghum), its sugary sap (sweet sorghum) or as a forage (forage sorghum) **(Fig.2)** (OECD, 2017).

Grain sorghum	sweet sorghum	forage sorghum

Fig. 2.Types of Sorghum

Cultivated sorghum is only one member of the genus *sorghum*, made up of 25 species and separated into five taxonomic sections: *Chaetosorghum, Heterosorghum, Parasorghum, Stiposorghum* and *Eusorghum*. Agronomically important *Eusorghum* species and include cultivated sorghum, its wild progenitor (*Sorghum bicolor* [L.] Moench subsp. *verticilliflorum* [Steud.] de Wet ex Wiersema & J. Dahlb.), Sudan grass (*Sorghum bicolor* notho subsp. *drummondii* [Steud.] de Wet ex Davidse), and weedy relatives such as Johnsongrass (*Sorghum halepense* [L.] Pers.), shattercane (a feral form of *Sorghum bicolor* notho subsp. *drummondii* [Steud.] de Wet ex Davidse) and *S. propinquum* (Kunth) Hitchc. The division of cultivated sorghum into subspecies and races over the past century has been somewhat archaic, with many competing classifications that are not properly validated (OECD, 2017). Synonyms are often used even at the species level. One such example is the ongoing use of *Sorghum caffrorum* and *Sorghum vulgare* by agencies throughout the world to indicate *Sorghum bicolor.* Competing names and priorities were considered and three subspecies were validated for *S. bicolor*: *S. bicolor* subsp. *bicolor*, *S. bicolor* subsp. *verticilliflorum* and *S. bicolor* subsp. *drummondii*. *S. bicolour* subsp. *bicolor* comprises the cultivated sorghums; *S. bicolor* subsp. *verticilliflorum* comprises annual wild relatives of cultivated sorghum native to Africa, Madagascar, the Mascarenes, and introduced varieties to India, Australia and the Americas; *S. bicolor* subsp. *drummondii* comprises annual weedy derivatives arising from hybridisation of cultivated sorghum and *S. bicolor* subsp. *verticilliflorum* (OECD, 2017).

Parasorghum includes five species (*S. grande, S. leiocladum, S. matarankense, S. nitidum,* and *S. timorense*);
Stiposorghum contains 10 species (*S. amplum, S. angustum, S. brachypodum, S. bulbosum, S. ecarinatum, S. exstans, S. interjectum, S. intrans, S. plumosum* and *S. stipoideum*), *Chaetosorghum* (*S. macrospermum*) and *Heterosorghum* (*S. laxiflorum*) are monotypic (Lazarides *et al.,* 1991). Harlan and de Wet (1972) and de Wet (1978) further classified and recognized three species in the subgenera *Eusorghum* (*S. halepense, S. propinquum, and S. bicolor*) representing all annual wild, weedy and cultivated taxa. *S. bicolor* further divided into three subspecies *S. bicolor* subsp. *bicolor*, *drummondii* and *verticilliflorum* (de Wet, 1978; Mann *et al*., 1983). *Sorghum halepense* and *Sorghum propinquum* are wild sorghums, and *Sorghum bicolor* subsp. *drummondii* and *verticilliflorum* are annual weeds. *Sorghum bicolor* subsp. *bicolor* contains all the cultivated sorghums.

It was believed that there were 20 to 30 species of genus *Sorghum* that are recognized until now, and these are classified into five sections: *stiposorghum, parasorghum, eu-sorghum, heterosorghum* and *chaetosorghum*. Under the section *eu-sorghum*, three species are recognized: *S halepense* (L.) Pers. occurring in India, *S. propinquum* (Kunth) Hitchc found in Southeast Asia and *S. bicolor* (L.) Moench, which originated in Africa (De Wet, 1978). All classified under genus *Sorghum*. De Wet's recognized *S. bicolor* (L.) Moench representing all annual cultivated, wild and weedy sorghums along with two rhizomatous taxa, *S. halepense* and *S. propinquum*. All types of the *S. bicolor* (the primitives) propagated with seeds except the rhizomatous taxa's which reproduces through both seed and rhizo reproduction. Sorghum bicolor was further broken down into three subspecies: *S. bicolor* sub sp *bicolor*, *S. bicolor* sub sp *drummondii* and *S. bicolor* sub sp *verticilliflorum*. The cultivated sorghums are classified as *S. bicolor* sub sp *bicolor* and represented by agronomic types such as grain sorghum, sweet sorghum, Sudan grass and broomcorn (Wikipedia, 2023)

Sorghum or broomcorn is a genus of about 25 species of flowering plants in the grass family (Poaceae). Some of these species are grown as cereals for human consumption, in pastures for animals as fodder, and as bristles for brooms. Sorghum grain is a nutritious food rich in protein, dietary fiber, B vitamins, and minerals Seventeen of the 25 species are native to Australia, with the range of some extending to Africa, Asia, Mesoamerica, and certain islands in the Indian and Pacific Oceans (Wikipedia, 2023).

Synonyms for *Sorghum bicolor* are numerous **(Table 1)** (Inspection, 2021).

Table 1. Synonyms for *Sorghum bicolor*

1)	*Andropogon arundinaceus* Willd.
2)	*Andropogon drummondii* Steud.
3)	*Andropogon sorghum* (L.) Brot.
4)	*Andropogon stapfii* Hook. f.
5)	*Andropogon subglabrescens* Steud.
6)	*Andropogon verticilliflorus* Steud.
7)	*Holcus bicolor* L.
8)	*Holcus cernuus* Ard.
9)	*Holcus dochna* Forssk
10)	*Holcus durra* Forssk
11)	*Holcus saccharatus* L.

12)	*Holcus sorghum* L.
13)	*Milium nigricans* Ruiz & Pav.
14)	*Panicum caffrorum* Retz
15)	*Rhaphis arundinacea* Desv.
16)	*Sorghum aethiopicum* (Hack.) Rupr. ex Stapf
17)	*Sorghum arundinaceum* (Desv.) Stapf
18)	*Sorghum basutorum* Snowden
19)	*Sorghum brevicarinatum* Snowden
20)	*Sorghum caffrorum* (Thunb.) P. Beauv.
21)	*Sorghum caudatum* (Hack.) Stapf
22)	*Sorghum cernuum* (Ard.) Host
23)	*Sorghum conspicuum* Snowden
24)	*Sorghum coriaceum* Snowden
25)	*Sorghum dochna* (Forssk.) Snowden
26)	*Sorghum × drummondii* (Steud.) Millsp. & Chase
27)	*Sorghum durra* (Forssk.) Stapf
28)	*Sorghum elegans* (Körn.) Snowden
29)	*Sorghum gambicum* Snowden
30)	*Sorghum guineense* Stapf
31)	*Sorghum hewisonii* (Piper) Longley
32)	*Sorghum japonicum* (Hack.) Roshev.
33)	*Sorghum lanceolatum* Stapf
34)	*Sorghum macrochaeta* Snowden
35)	*Sorghum margaritiferum* Stapf
36)	*Sorghum melaleucum* Stapf
37)	*Sorghum mellitum* Snowden
38)	*Sorghum membranaceum* Chiov.
39)	*Sorghum miliiforme* (Hack.) Snowden
40)	*Sorghum nervosum* Besser ex Schult. & Schult. f.
41)	*Sorghum nigricans* (Ruiz& Pav.) Snowden
42)	*Sorghum niloticum* (Stapf ex Piper) Snowden
43)	*Sorghum notabile* Snowden
44)	*Sorghum pugionifolium* Snowden
45)	*Sorghum roxburghii* Stapf
46)	*Sorghum saccharatum* (L.) Moench
47)	*Sorghum simulans* Snowden
48)	*Sorghum splendidum* (Hack.) Snowden
49)	*Sorghum stapfii* (Hook. f.) C. E. C. Fisch.
50)	*Sorghum subglabrescens* (Steud.) Schweinf.& Asch.
51)	*Sorghum sudanense* (Piper) Stapf.
52)	*Sorghum technicum* Batt.& Trab.
53)	*Sorghum usambarense* Snowden
54)	*Sorghum verticilliflorum* (Steud.) Stapf
55)	*Sorghum virgatum* (Hack.) Stapf
56)	*Sorghum vogelianum* (Piper) Stapf
57)	*Sorghum vulgare* Pers.

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Synonyms (100) for *Sorghum bicolor* are given in **Table 2** (Wikipedia, 2023)

Table 2. Synonyms for *Sorghum bicolor*

1)	*Agrostis nigricans* (Ruiz & Pav.) Poir.
2)	*Andropogon besseri* Kunth
3)	*Andropogon bicolor* (L.) Roxb.
4)	*Andropogon caffrorum* (Thunb.) Kunth
5)	*Andropogon compactus* Brot.
6)	*Andropogon dulcis* Burm.f.
7)	*Andropogon niger* (Ard.) Kunth
8)	*Andropogon saccharatrus* Kunth
9)	*Andropogon saccharatus* (L.) Raspail
10)	*Andropogon sorghum* (L.) Brot.
11)	*Andropogon subglabrescens* Steud.
12)	*Andropogon truchmenorum* Walp.
13)	*Andropogon usorum* Steud.
14)	*Andropogon vulgare* (Pers.) Balansa
15)	*Andropogon vulgaris* Raspail
16)	*Holcus arduinii* J.F.Gmel.
17)	*Holcus bicolor* L.
18)	*Holcus cafer* Ard.
19)	*Holcus caffrorum* (Retz.) Thunb.
20)	*Holcus cernuus* Ard.
21)	*Holcus cernuus* Muhl. nom. illeg.
22)	*Holcus cernuus* Willd. nom. illeg.
23)	*Holcus compactus* Lam.
24)	*Holcus dochna* Forssk
25)	*Holcus dora* Mieg
26)	*Holcus duna* J.F.Gmel.

27) *Holcus durra* Forssk
28) *Holcus niger* Ard.
29) *Holcus nigerrimus* Ard.
30) *Holcus rubens* Gaertn.
31) *Holcus saccharatus* var. *technicus* (Körn.) Farw.
32) *Holcus sorghum* L.
33) *Holcus sorghum* Brot. nom. illeg.
34) *Milium bicolor* (L.) Cav.
35) *Milium compactum* (Lam.) Cav.
36) *Milium maximum* Cav.
37) *Milium nigricans* Ruiz & Pav.
38) *Milium sorghum* (L.) Cav.
39) *Panicum caffrorum* Retz
40) *Panicum frumentaceum* Salisb. nom. illeg.
41) *Rhaphis sorghum* (L.) Roberty
42) *Sorghum abyssinicum* (Hack.) Chiov. nom. illeg.
43) *Sorghum ankolib* (Hack.) Stapf
44) *Sorghum anomalum* Desv.
45) *Sorghum arduinii* (Gmel.) J.Jacq.
46) *Sorghum basiplicatum* Chiov.
47) *Sorghum basutorum* Snowden
48) *Sorghum caffrorum* (Retz.) P.Beauv.
49) *Sorghum campanum* Ten. & Guss.
50) *Sorghum caudatum* (Hack.) Stapf
51) *Sorghum centroplicatum* Chiov.
52) *Sorghum cernuum* (Ard.) Host
53) *Sorghum compactum* Lag.
54) *Sorghum conspicuum* Snowden
55) *Sorghum coriaceum* Snowden
56) *Sorghum dochna* (Forssk.) Snowden
57) *Sorghum dora* (Mieg) Cuoco
58) *Sorghum dulcicaule* Snowden
59) *Sorghum dura* Griseb.
60) *Sorghum durra* (Forssk.) Batt. & Trab.
61) *Sorghum elegans* (Körn.) Snowden
62) *Sorghum eplicatum* Chiov.
63) *Sorghum exsertum* Snowden
64) *Sorghum gambicum* Snowden
65) *Sorghum giganteum* Edgew.
66) *Sorghum glabrescens* (Steud.) Schweinf. & Asch.
67) *Sorghum glycychylum* Pass.
68) *Sorghum guineense* Stapf
69) *Sorghum japonicum* (Hack.) Roshev.
70) *Sorghum margaritiferum* Stapf
71) *Sorghum medioplicatum* Chiov.
72) *Sorghum melaleucum* Stapf
73) *Sorghum melanocarpum* Huber
74) *Sorghum mellitum* Snowden
75) *Sorghum membranaceum* Chiov.
76) *Sorghum miliiforme* (Hack.) Snowden
77) *Sorghum nankinense* Huber
78) *Sorghum nervosum* Besser ex Schult. & Schult.f.
79) *Sorghum nervosum* Chiov. nom. illeg.
80) *Sorghum nigricans* (Ruiz& Pav.) Snowden
81) *Sorghum nigrum* (Ard.) Roem. & Schult.
82) *Sorghum notabile* Snowden
83) *Sorghum pallidum* Chiov. nom. illeg.
84) *Sorghum papyrascens* Stapf
85) *Sorghum rigidum* Snowden
86) *Sorghum rollii* Chiov.
87) *Sorghum roxburghii* var. *hians* (Hook.f.) Stapf
88) *Sorghum saccharatum* Host nom. illeg.
89) *Sorghum saccharatum* (L.) Pers. nom. illeg.
90) *Sorghum sativum* (Hack.) Batt. & Trab.
91) *Sorghum schimperi* (Hack.) Chiov. nom. illeg.
92) *Sorghum simulans* Snowden
93) *Sorghum splendidum* (Hack.) Snowden
94) *Sorghum subglabrescens* (Steud.) Schweinf. & Asch.
95) *Sorghum tataricum* Huber
96) *Sorghum technicum* (Körn.) Batt. & Trab.
97) *Sorghum technicum* (Körn.) Roshev.
98) *Sorghum truchmenorum* K.Koch
99) *Sorghum usorum* Nees *Sorghumvulgare* Pers. nom. illeg.

All the cultivated sorghum taxa of the world have been classified by inflorescence type, grain and glumes into five races (*durra, bicolor, caudatum, kaffir* and *guinea*) and intermediates involving all of the pair-wise combinations of the basic races (de Wet, 1978; Harlan and deWet, 1972). The entire races were differentiated morphologically based on their inflorescence, grain and glumes. The race *bicolor* has its grain elongated, with glumes clasping the grain, which may be completely covered or exposed. This race is mostly grown west of the Rift valley and also on a minor scale almost everywhere in Africa.

Guinea is primarily West African with a secondary centre in Malawi and Tanzania. The grainis flattened dorso-ventrally, twisting at maturity 90 degrees between glumes that are nearly as long as or longer than the grain. The *caudatum* grain is asymmetrical, with glumes half the length of the grain or less. This race is most abundant in east Nigeria, Sudan and Uganda. *Kafir* is mostly a race of east and Southern Africa. It has symmetrical grain, with glumes of variable length clasping the grain. *Durra* is dominant in Ethiopia and westward across the continent, covering the driest parts near the Sahara. Itsgrain is rounded and the glumes are very wide (House, 1985). There are five basic races and ten intermediate races under cultivated taxa based on fundamental spikelet types (Hariprasanna and Patil, 2015).

For many years, sorghum breeders have classified cultivated sorghum into races or working groups according to morphological characteristics. A system was then developed dividing cultivated sorghum into five basic interfertile races (*bicolor, kafir, caudatum, durra* and *guinea*) and ten intermediate races, based on floral morphology. This classification system was widely adopted. A more detailed description of the characteristics of each of the five main races of cultivated sorghum can be found in Table 3. Diagrams of spikelet and head types of the races are given in Fig. 3 (Snowden, 1936; Harlan and de Wet, 1972; OECD, 2017).

Table 3. Sorghum race characteristics

Bicolor: Open inflorescences with pendulous branches. Long clasping glumes. Elliptic grain.
Guinea: Large, open inflorescences with pendulous branches. Long, separated glumes that expose grains. Obliquely twisted grains.
Durra: Compact inflorescences. Flat, ovate shaped sessile spikelets. Middle-ceased lower glumes. Distinct texture of tip of lower glume.
Caudatum: Compact to open inflorescences. Grains with one side flat, opposite side curved. Shorter glumes that expose grains.
Kafir: Moderately compact, cylindrical inflorescences. Elliptic spikelets. Tightly clasping, long glumes.

Fig.3: Variations in panicle morphology of the five primary sorghum races in the association mapping panel: IS 608 has semi-compact panicles; IS 7250 has loose panicles; IS4631, IS4092 and IS 12937 have compact panicles

Harlan and de Wet (1972) developed a simplified classification of cultivated sorghum that proved to be of real practical utility for sorghum researchers. They classified *Sorghum bicolor* (L.) Moench, subspp. *bicolor* into five basic and ten hybrid races (Table 4).

Table 4. Five basic and ten hybrid races of Sorghum

Basic races	Intermediate/hybrid races
1. Race *bicolor* (B)	6. Race *guinea-bicolor* (GB)
2. Race *guinea* (G)	7. Race *caudatum-bicolor* (CB)
3. Race *caudatum* (C)	8. Race *kafir-bicolor* (KB)
4. Race *kafir* (K)	9. Race *durra-bicolor* (DB)
5. Race *durra*(D)	10. Race *guinea-caudatum* (GC)
	11. Race *guinea-kafir* (GK)
	12. Race *guinea-durra* (GD)
	13. Race *kafir-caudatum* (KC)
	14. Race *durra-caudatum* (DC)
	15. Race *kafir-durra* (KD)

The descriptors for five basic races in sorghum are given in Table 5 and Fig. 4 (Harlan and de Wet, 1972).

Table 5. Descriptors for five basic races of Sorghum

1.	***Bicolor***: Grain elongate, sometimes slightly obovate, nearly symmetrical dorsoventrally, glumes clasping the grain, which may be completely covered or exposed as much as one-fourth of its length at the tip, spikelets persistent.
2.	**Guinea:** Grain flattened dorsoventrally, sub-lenticular in outline, twisting at maturity nearly 90° between gaping involute glumes that are nearly as long as to longer than the grain. They are easily distinguishable by the presence of open glumes.
3.	***Caudatum***: Grain markedly symmetrical, the side next to the lower glume flat or in extreme cases somewhat concave, the opposite side rounded and bulging, the persistent style often at the tip of a beak pointing towards the lower glume, glumes half the length of the grain or less.
4.	***Kafir***: Grain approximately symmetrical, more or less spherical, glumes clasping and variable in length.
5.	***Durra***: Grain rounded obovate, wedge-shaped at the base and broadest slightly above the middle; glumes very wide, the tip of a different texture from the base and often with a transverse crease across the middle.

All 15 races of cultivated sorghum can be identified by mature spikelets alone, although head type is sometimes helpful. This classification is clear and simple and practically all of the variation in cultivated sorghum can be accounted for by the five basic races and their intermediate combinations. The intermediate races involving *guinea*, for example, have glumes that open partially and seeds that twist noticeably, but not as much as in pure *guinea*. Intermediate races involving *caudatum* have asymmetrical seeds, but the character is not as fully expressed as in pure *caudatum*. Other intermediate combinations can be recognized in a similar manner. The method is so sensitive that even three-way and possibly four-way combinations can also be recognized, but these are usually products of modern plant breeding and not part of the variation of indigenous varieties. If they occur in significant numbers, they could be best treated as subraces of the main races (Harlan and de Wet, 1972)

The distinguishing characteristics of the five interfertile domesticated sorghum races are given in Table 6 (Harlan and De Wet 1972; Inspection, 2021).

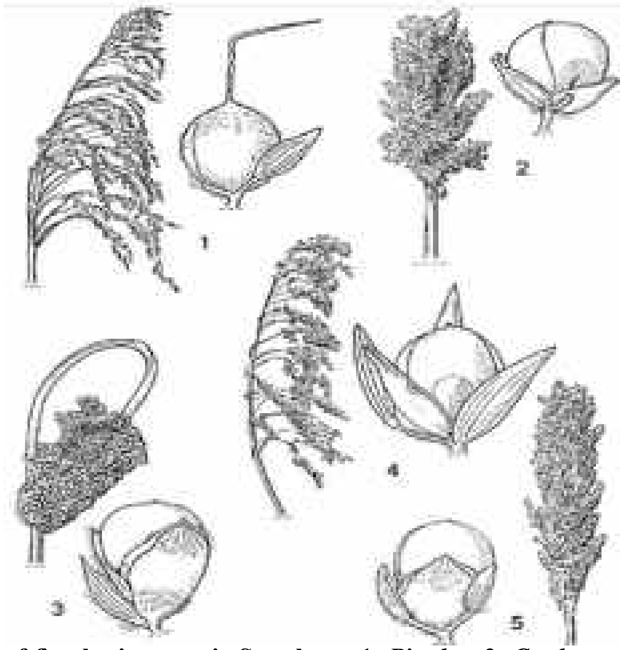


Fig. 4. Panicles and spikelets of five basic races in Sorghum: 1. *Bicolor*, 2. *Caudatum*, 3. Durra, 4. *Guinea*, 5. *Kafir*

Table 6. Characteristics of domesticated sorghum races

Race	Distinct Characteristics
Bicolor	• Open inflorescences with pendulous branches • Long, clasping glumes • Relatively small and elliptic grains
Kafir	• Moderately compact, cylindrical inflorescences • Elliptic spikelets • Tightly clasping, long glumes
Caudatum	• Compact to open inflorescences • Grains with one side flat, opposite side curved • Shorter glumes that expose grains
Durra	• Compact inflorescences • Flat, ovate shaped sessile spikelets • Middle-creased lower glume • Distinct texture on tip of lower glume
Guinea	• Large, open inflorescences with pendulous branches • Long, separated glumes that expose grains • Obliquely twisted grains

BOTANICAL DESCRIPTION

Growth Stages: Recognizing the key developmental stages of sorghum can aid in making critical management decisions. The stages are based on sorghum structures as they develop over the life of the plant. A sorghum plant has 10 official stages of growth and development, starting with emergence – Stage 0 – and ending with the physiological maturity of the grain, Stage 9 (Fig. 5) (GD, 2023). During the vegetative stage of the sorghum plant, the number of leaves is often used to determine the stage of the plant. Grain sorghum leaves are numbered by counting the fully expanded leaves that have a developed collar. When counting leaves, keep in mind that the first leaf is short with a rounded tip and leaves alternate from one side of the stalk to the other. Once sorghum has produced approximately five fully expanded leaves, counting can become difficult because lower leaves will die and fall off the plant. For instance, the first leaf likely will fall off the plant within 25 days of emergence (GD, 2023).

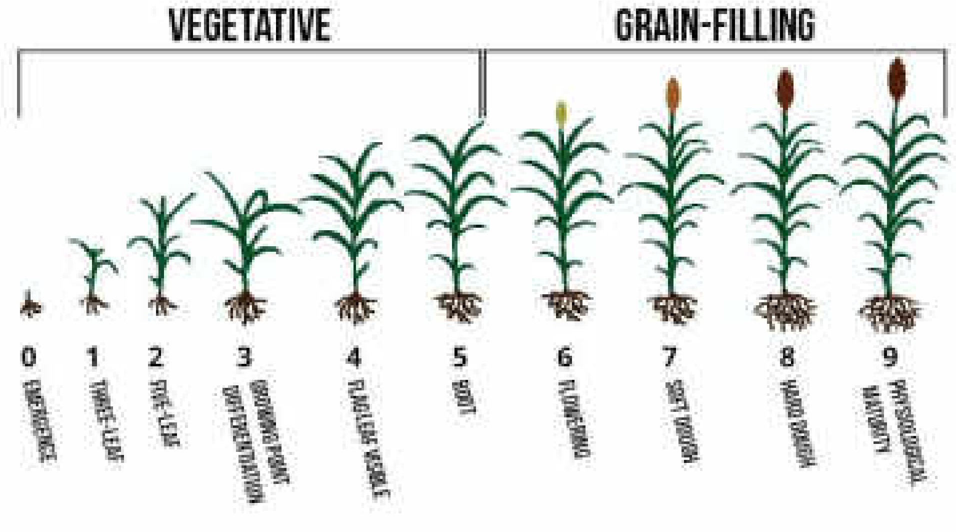


Fig. 5. Stages of growth in Sorghum

The following are descriptions of each growth stage along with timely management suggestions (Fig. 6) (GD,2023):

Stage 0: Emergence: The plant is visible when the first leaf, known as the coleoptile leaf, breaks through the soil surface. The coleoptile leaf is shorter than the later emerging leaves and has a rounded leaf tip. Emergence time can range from three to 14 days, depending largely on soil temperature, moisture, seeding depth and seedling vigor.

Stage 1: Three-Leaf: The collar of the third leaf is visible. Note that once a leaf's collar forms, the leaf no longer expands. This stage occurs 10 to 15 days after emergence, depending on weather conditions, when the plant is typically 3 to 4 inches tall.

Stage 2: Five-Leaf: The collar of the fifth fully expanded leaf is visible, and the growing point is at or just below the soil surface. This stage occurs approximately 20 to 25 days after emergence when the plant is 7 to 9 inches tall. Farmers should apply most post-emergent herbicides at or before this time. Sidedress fertilizer applications are best made at this stage or within the following 10 to 15 days.

Stage 3: Growing Point Differentiation (GPD): The plant is entering a rapid period of growth. The growing point can be found just above the ground by splitting the stalk, and the number of seeds per head will be determined over the next couple of weeks. This stage typically occurs 30 to 40 days after emergence, when the plant is 12 to 15 inches tall. At this stage, one or two of the bottom leaves may have fallen off, and tillers may be present at the base of the plant. Prior to GPD, the plant can withstand considerable stress with minimum effect on yield. However, stress during GPD can affect the potential number of seeds per head at flowering. Stage 3 is a key time to apply irrigation if soil moisture conditions are dry and irrigation is available.

Stage 4: Flag Leaf Visible: The last leaf to emerge prior to heading is called the flag leaf, which is shorter than the preceding leaves. The sorghum plant is in the flag leaf stage when the leaf tip is visible in the whorl. The last two or three leaves will fully expand during this period. Typically, the plant progresses from the flag leaf to the boot stage in 5 to 7 days.

Stage 5: Boot: The boot stage is when the sorghum panicle, also known as the head, is in the flag leaf sheath and can be seen as a bulge or swelling. Leaf collars of all leaves are visible, and the panicle is pushed up through the flag leaf collar by the upper stalk, known as the peduncle. The length of the peduncle can be affected by stress at this time and is influenced by hybrid genetics. With most grain sorghum hybrids, the boot stage occurs approximately 50 to 60 days after emergence. Moisture and heat stress during the boot stage and for the next 14 days will significantly lower yield. The plant progresses from the boot stage to the heading stage in 3 to 5 days.

Heading (Not An Official Stage): Heading occurs when the panicle becomes visible as it emerges from the flag leaf sheath. Sorghum is considered "headed" when 50% of the panicles in a field are visible. The plant can progress from heading to mid-bloom very quickly. In fact, some hybrids begin blooming as soon as the panicle has completely emerged from the leaf sheath.

Stage 6: Flowering: Flowering or blooming is the most critical stage in the life of the sorghum plant. A plant begins flowering from the top of the panicle and progresses downward. A field of sorghum is in the flowering stage when blooming has progressed halfway down the panicle in 50% of the plants. At this stage, the peduncle is still elongating, and it typically takes 4 to 9 days for a single panicle to complete the flowering process. Hybrids are rated on their maturity largely based on the length of time the plant takes to reach the flowering stage.

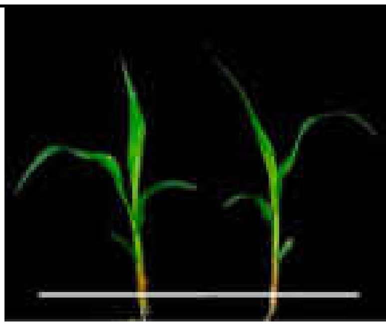
Milk (Not An Official Stage): Grain begins forming as soon as flowering and pollination are complete. The grain or kernel quickly expands and contains a milky fluid. At this point, the sorghum is in the grain fill period that will not be completed until physiological maturity is reached. The milk stage usually lasts 7 to 10 days.

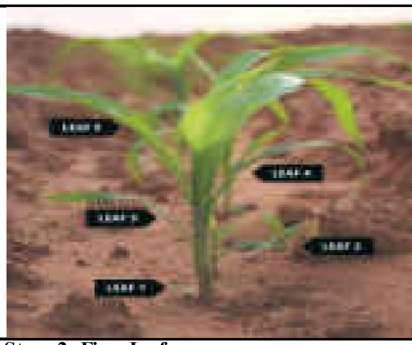
Stage 7: Soft Dough: Sorghum reaches the soft dough stage when the grain can be crushed between the thumb and index finger but no longer contains a milky liquid. At this stage, starch is rapidly accumulating, 50% of the grain's final weight has been achieved, and the whole plant moisture is approximately 65-68%. Stress at this time can significantly lower yield. By the end of the stage, the grain has colored, and the sorghum is ready to harvest as silage. The soft dough stage will last 7 to 10 days or until the grain can no longer be crushed between the thumb and index finger.

Stage 8: Hard Dough: At the hard dough stage, grain has reached 75 percent of its final dry weight, and nutrient uptake is almost complete. The grain can no longer be crushed between the thumb and index finger. The seed coat is no longer green and has turned its final color, which can be white, tan, bronze or red. The total moisture content of the plant is now decreasing daily, and water stress during this time tends to promote lodging. The hard dough stage typically lasts 10 to 14 days.

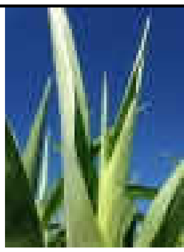
Stage 9: Physiological Maturity: At this stage, the grain has achieved its maximum dry weight. Physiological maturity is recognized by a dark spot or black layer on the bottom of the kernel. Grain moisture content typically ranges between 25-35%. Desiccants can be safely used to aid in harvest without reducing grain yield. The total time from flowering to physiological maturity is approximately 40 to 45 days.

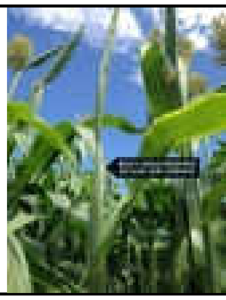

Stage 0: Emergence


Stage 1: Three-Leaf


Stage 2: Five-Leaf


Stage 3: Growing Point Differentiation (GPD)


Stage 4: Flag Leaf Visible


Stage 5: Boot


Stage 5: Boot


Heading (Not An Official Stage)


Stage 6: Flowering


Stage 6: Flowering


Milk(Not An Official Stage)


Stage 7: Soft Dough

		
Stage 8: HARD DOUGH	Stage 9: Physiological Maturity	

Fig. 6. Growth stages of Sorghum

Table 7. Sorghum Growth Stages

I	Emergence, depending on air temperature and soil moisture between 3 & 10 days after seeding
II	Collar of third leaf visible
III	Collar of fifth leaf visible, ~21 days after emergence
IV	Change from vegetative to reproductive growth, 7 to 10 leaves expanded, floral initiation
V	All leaves fully expanded
VI	Half of plants blooming (in field, or individual plant)
VII	"Soft dough": accumulation of ~50% half grain dry weight
VIII	"Hard dough": accumulation of ~75% half grain dry weight, nutrient uptake complete
IX	Physiological maturity: maximum dry weight of plant reached

Description: Sorghum is annual/ perennial grass, the roots are adventitious and fibrous, stem is erect and made up of nodes and internodes, the pith may be sweet, juicy or dry. The leaves are 7 and 28 arranged alternating to opposite side with parallel venation. Presence of waxy layer limits the water loss. The panicle varies loose to compact, in some varieties panicle remain surrounded by sheath and sometimes peduncle recurred, giving pendent head referred as "goose neck". Panicle consists of spiklets in pairs; the sessile is hermaphrodite and fertile while other pedicillate is sterile. The sessile spiklet consists of inner and outer glumes enclosing two flowers, upper one is perfect and lower one is reduced. The perfect flower has thin narrow hairy lemma and small pelia enclosing three stamen, two lodicules and bifurcated feathery (brush like) stigma. The pedicillate flower is without pelia and ovary. Grain is caryopsis, endosperm is starchy, and embryo consists of plumule, coleoptiles, radical coleorhizae referred as scutelum (Agriinfo, 2016). Sorghum has a well-developed root system and in addition to its subterranean root system, sorghum forms strong aerial roots permeating through the soil and ensuring better stability. The stem is strong, hard, smooth, and divided by nodes and grows up to 1–1.8 m, but sweet sorghums and highbiomass sorghums are taller (2.5–4 m). Sorghum leaves are 7 and 28 in number arranged alternating to opposite sides with parallel venation. The leaves are 50–100 mm wide and 0.5–0.8 m long depending upon the genotype. Leaves and stems are often covered with a wax layer which is an adaptation mechanism to tolerate drought and insect attacks. The panicle varies fom loose to compact; in some varieties the panicle remains surrounded by sheath, although this is not desirable fom an economic yield point of view. In some genotypes the peduncle is recurred resulting in a pendant head referred to as "goose neck". The sorghum panicle consists of spikelets in pairs, sessile and pedicillate types; the sessile is hermaphrodite and fertile and the other pedicillate contains only anthers. The grain is caryopsis; the endosperm is starchy; the embryo consists of plumule, coleoptiles, and radical coleorhizae referred to as scutellum (Kumar, 2016).

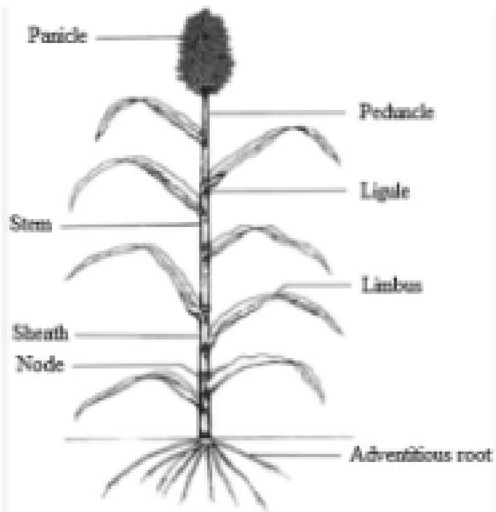


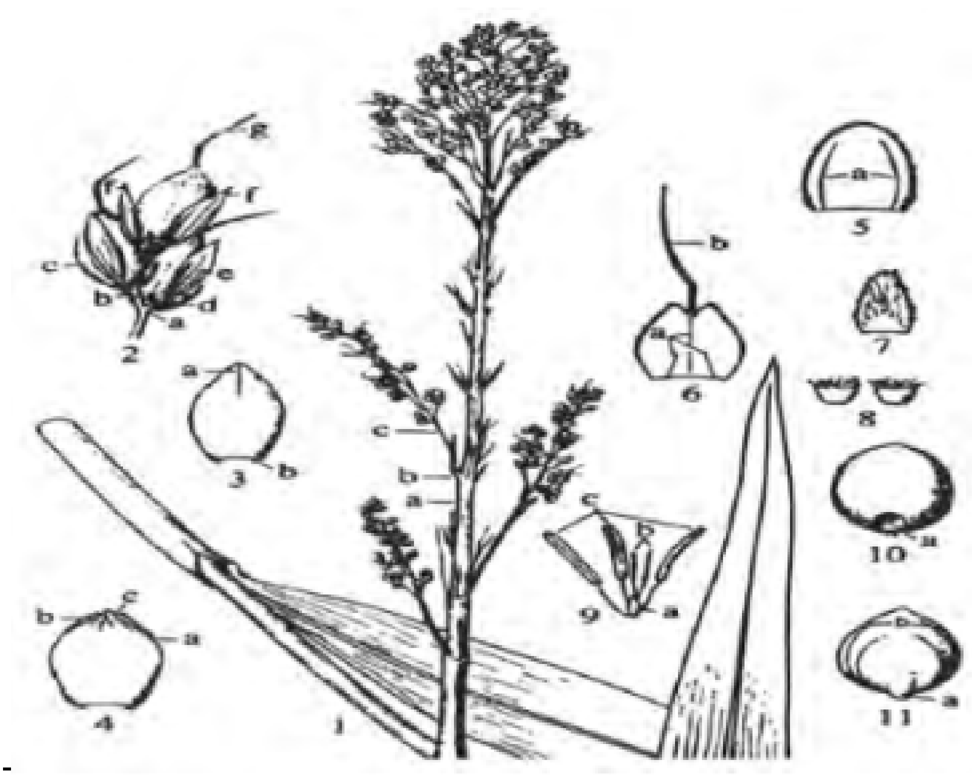
Fig. 7. Mature Sorghum plant

Cultivated sorghum is a cane-like grass with diverse morphology. Plant height ranges from 0.5 metres (m) to 6 m. Culms (stalks) are erect and range from slender to stout. Tillers (adventitious stems originating from the plant base) can range in quantity from none to profuse. Leaf blades vary from linear to lanceolate, and can be smooth or hairy, measuring up to 100 centimetres (cm) long and 10 cm wide with smooth to thinly pilose sheaths. The inflorescence consists of a single panicle with many racemes. Panicles may be either compact or open up to 50 cm long and 30 cm wide; panicle branches are stiffly ascending or spreading and pendulous, with the bottom branch being almost half as long as the panicle.

At maturity, racemes have one to eight nodes and can be either fragile or tough. Spikelets may be glabrous or hirsute, elliptic to obovate, and up to 6 mm long. Glumes (bracts) range from leathery to membranous, often with winged keels. Lower lemmas are approximately 6 mm long while upper lemmas are slightly shorter and often awned. Both upper and lower lemmas of sessile spikelets are somewhat ciliate and translucent (Snowden, 1936; Harlan and de Wet, 1972; OECD, 2017).

S. bicolor is a C_4 annual or short-lived perennial grass that typically has one generation per growing season. It can produce tillers (adventitious stems originating from the plant base) but not rhizomes. The culms (stalks) typically reach heights from 50 to over 240 cm and are 1 to 5 cm thick, sometimes branching above the base. The nodes are glabrous or have appressed pubescent hairs. The internodes are glabrous. The ligules are 1 to 4 mm long. The leaf blades are 5 to 100 cm long and 5 to 100 mm wide. The inflorescence (panicle) is 5 to 60 cm long, 3 to 30 cm wide, and may be open or contracted. The primary panicle branches are compound, terminating in racemes with 2 to 7 spikelet pairs. The sessile spikelets are bisexual and 3 to 9 mm in length. The glumes are coriaceous to membranous and glabrous to densely hirsute or pubescent. The keels on the glumes (bracts) are usually winged. The upper lemmas vary from being awnless to having a geniculate, twisted, 5 to 30 mm awn. The anthers are 2 to 3 mm long. The pedicels are 1 to 3 mm long. The pedicellate spikelets are 3 to 6 mm long and are usually shorter than the sessile spikelets. The pedicillate spikelets may be staminate or sterile. Domesticated sorghums produce large caryopses that are often exposed at maturity. Cultivars and environmental conditions affect the nutritional composition of the caryopses and the composition of their components including the pericarp (outer layer), the endosperm (storage tissue), and the germ (embryo). The protein content of the caryopsis ranges from 7.3 to 15.6%; fibre from 1.2 to 6.6%; lipids from 0.5 to 5.2%; and starch from 55.6 to 75.2% (Inspection, 2021). Sorghum used for grain has short panicles and panicle branches while sorghum used for forage is typically leafier, and late maturing. Sorghum used for grain typically grows 60 to 120 cm tall and is usually shorter than sorghums used for forage that can grow over 150 cm tall. Sudan grass and sorghum-Sudan grass hybrids are intermediate in height in between grain sorghums and forage sorghums (Inspection, 2021). *S. bicolor* is typically an annual, but some cultivars are perennial. It grows in clumps that may reach over 4 metres high. The grain is small, ranging from 2 to 4 mm in diameter. Sweet sorghums are sorghum cultivars that are primarily grown for forage, syrup production, and ethanol; they are taller than those grown for grain. *Sorghum bicolor* is the cultivated species of sorghum; its wild relatives make up the botanical genus *Sorghum* (Wikipedia, 2023). Sorghum is an upright, short-day, summer annual that is a member of the Poaceae family. The grass blades are flat, stems are rigid, and there are no creeping rhizomes. Sorghum has a loose, open panicle of short, few-flowered racemes. As seed matures, the panicle may droop. Glumes vary in color from red or reddish brown to yellowish and are at least three quarters as long as the elliptical grain. The grain is predominately red or reddish brown. Sorghums exhibit different heights and maturity dates depending on whether they are grain sorghums (*Sorghum bicolor* ssp. *bicolor*), forage sorghums *(Sorghum bicolor)*, Sudangrass *(Sorghum bicolor* ssp. *drummondii*), or sorghum-Sudan grass hybrids *(Sorghum bicolor* x *Sorghum bicolor var. sudanense)*. Growth characteristics also vary depending on the location grown, inputs, and agronomic practices. In general, forage sorghums are taller plants with later maturity dates and more vegetative growth than grain sorghums. Sudan grass and sorghum-Sudan grass hybrids fall in between grain sorghums and forage sorghums in height (USDA, 2023). Sorghum is a strong grass and usually grows to a height of 0.6 to 2.4 metres, sometimes reaching as high as 4.6 metres. Stalks and leaves are coated with a white wax, and the pith, or central portion, of the stalks of certain varieties is juicy and sweet. The leaves are about 5 cm broad and 76 cm long. The tiny flowers are produced in panicles that range from loose to dense; each flower cluster bears 800–3,000 kernels. The seeds vary widely among different types in colour, shape, and size, but they are smaller than those of wheat (Britannica, 2023). Sorghum is a tall, erect, annual grass that typically grows to a height of 1-2 meters. It has long, narrow leaves and produces large, compact clusters of grain on top of its stems. The grains are typically small and round, with a hard outer layer that is difficult to remove. Sorghum plants come in many different colors, including red, brown, white, and yellow, and some varieties have a sweet taste (Plantvillage, 2023). Sorghum is an annual or perennial grass. The root system is fibrous. The stem is erect with leaves alternating on opposite sides on nodes. Basal tillers are formed at the first node. No. of leaves range from 7-28. The leaves have drought tolerance because of:-¬Small size of stomata cells during drought. ¬A waxy layer which limits water loss. And ¬Presence of motor cells which cause rolling of leaves under drought stress. Inflorescence is raceme type (Panicle). The panicle varies from being very loose to compact. The panicle consists of spikelets which occurs in pairs. One pair is sessile, hermaphrodite and fertile. Other pair is pedicellate, male and sterile. The sessile spikelet has 2 glumes with 2 florets. One is fertile, bisexual consists of a membranous lemma and a small thin delicate palea. Two lodides are present adjacent to fertile lemma. Lodicules are fleshy and truncate. Stamens: 3. Pistil: an ovary with two long styles with a feathery stigma. Two leathery boat shaped glumes enclosing 2 florets. The lower floret is represented by lemma and upper floret is staminate with short awned lemma. Palea: absent. Stamens: 3. Pistil: absent. Flowering occurs 30-40 days after germination *i.e.*, 2-4 days after emergence of panicle from boot leaf. Flowering starts in sessile spikelets at tip of inflorescence and progresses towards bottom. The pedicellate spilkelets open later and complete flowering earlier than in sessile spikelets. Sorghum is a selfpollinated crop but 2-10% cross pollination may occur. The anthers & stigmas push out as the glumes open. The anthers dehisce and release pollen. Receptivity of stigma starts 2 days before opening and remains for several days. Sorghum is a short day plant and hastened by short day light periods and high temperatures. After fertilization, embryo is developed. The deposition of starch grains begin about 10 days after fertilization. Seed development is in 3 stages: milk stage, soft dough stage and hard dough stage. The seed consists of pericarp (outer coat, 6% by weight), endosperm (storage tissue 84%) and embryo (germ, 10%). Embryo is made of 70 % fat and 13% in the grain (Susmitha, 2023)

Sorghum is an annual plant, monoecious, tall, with one to many tillers originating from the base or stem nodes. Roots are concentrated in the top of the soil but sometimes extending to twice that depth, spreading laterally. The stem (culm) is solid, usually erect; leaves alternate, simple, long leaf sheath often with waxy bloom with band of short white hairs at base near attachment and articulated, ligule short, blade lanceolate or linear-lanceolate, initially erect later curving, margins flat or wavy (Fig.7) (Balakrishna and Bhat, 2016). Inflorescence is a terminal panicle comes out of flag-leaf sheath at heading time. Panicle is long, compact or loose, open. Rachis is short or long with primary, secondary, and sometimes tertiary branches with spikelets in pairs and in groups of three at the ends of branches. Spikelet is sessile and bisexual or pedicelled and male or sterile with 2 florets; sessile spikelet is long with glumes approximately in equal length, lower glume is veined usually with a coarse keel-like vein on each side, upper glume usually narrower and more pointed with central keel for part of its length, lower floret consisting of a lemma only, upper floret bisexual with lemma cleft at apex, with or without kneed, twisted awn, palea when present is small and thin, 2 lodicules, 3 stamens, ovary superior, 1-celled with 2 long styles ending in feathery stigmas. Pedicelled spikelet is persistent or deciduous, smaller and narrower than sessile spikelet, often consisting of only two glumes, sometimes with lower floret consisting of lemma only and upper floret with lemma, 2 lodicules and 3 stamens (Fig.8) (Balakrishna and Bhat, 2016). ‒Fruit is a caryopsis (grain) partially covered by glumes, round and bluntly pointed consists of embryo; endosperm and seed coat consists of pericarp and testa (Fig.9). Coleoptiles and roots emerge from the germinating seeds (Balakrishna and Bhat, 2016).



1. Part of panicle: a. Internode of rachis, b. Node with branches, c. Branch with several Recemes. 2. Raceme: a. Node, b. Internode, c. Sessile spikelet, d. Pedicel, e. Pedicelled spikelet, f. Terminal pedicelled spikelets, g. Awn. 3. Upper glome: a. Keel, b. Incurved margin. 4. Lower glume: a. Keel, b. Keel wing, c. Minute tooth terminating keel. 5. Lower lemma: a. Nerves. 6. Upper lemma: a. Nerve, b. Awn. 7. Palea. 8. Lodicules. 9. Flower: a. Ovary, b. Stigma, c. Anthers. 10. Grain: a. Hilum 11. Grain: a. Embryo mark, b. Lateral lines

Fig. 8. Inflorescence and spikelets of Sorghum

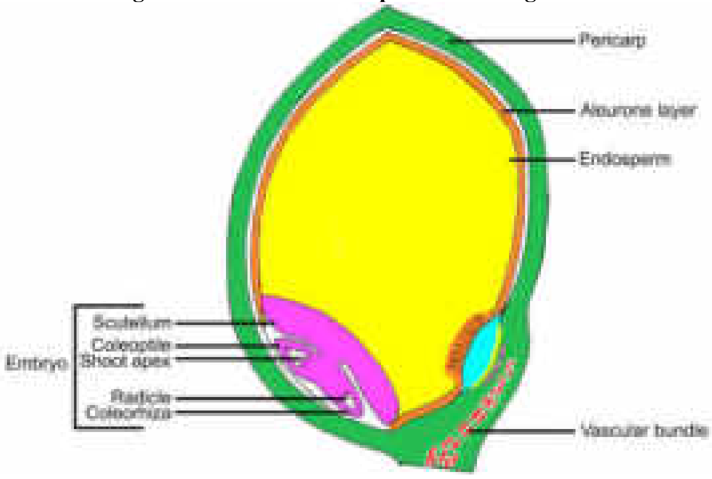
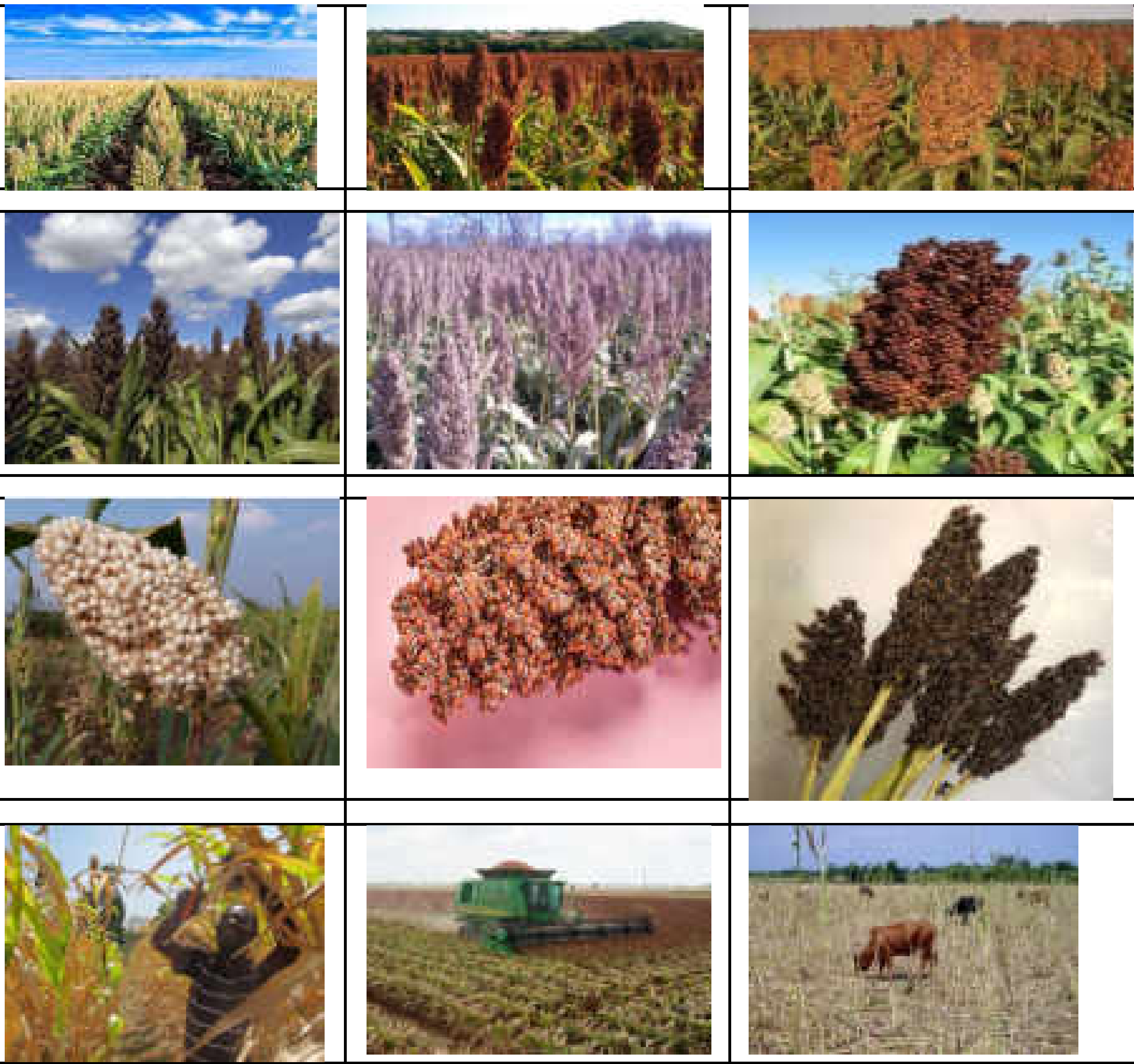


Fig.9. Caryopsis (grain) of sorghum in longitudinal section, 20 days after flowering





Hand-harvesting sorghum	Mechanized sorghum grain harvesting	Cattle grazing on sorghum stalks in a field

Fig.10. Botanical Description

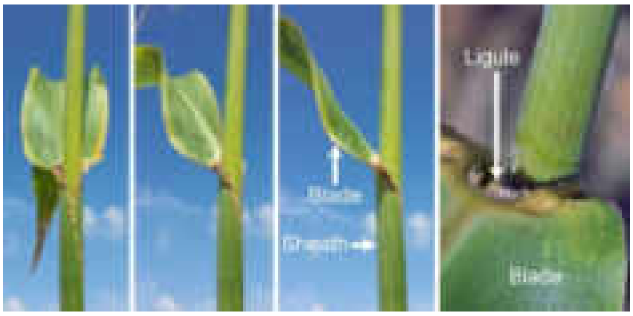


Fig.11 : Sorghum foliage leaves. Left three panels: Three different views of a leaf showing the sheath and blade. Right: Close-upof a leaf showing the ligule made up of hairs and a blade

Fig.12 : Two sides of agrain of sorghum. The depression on oneside shows where the embryo is. The hilum on theother surface is the attachment point of the grain

Floral biology and pollination: The many racemes and spikelets that compose the panicle develop about 21 days after the onset of the reproductive phase. A single panicle may bear 6 000 florets in total. Spikelets along the racemes occur in sessile and pedicelled pairs. The sessile spikelets are fertile while the pedicelled spikelets are staminate and are formed on a short pedicel. The glumes of the sessile spikelets encase two florets. While the lower floret is sterile and consists of a lemma only, the upper floret is perfect, consisting of a lemma, two lodicules flanking the lemma, three stamens and a single-celled ovary with two plumose stigmas. Anthesis can begin as soon as the panicle begins to emerge from the culm, but usually begins several days later after the peduncle has reached its maximum growth. The first flower to bloom is the uppermost flower, and blooming continues down the panicle in a regular pattern. Sessile spikelets bloom first with pedicelled spikelets blooming two to four days later. Temperature, size of panicle and variety are the primary factors that determine duration of flowering, which is typically about one week, but varies from 2 to 15 days. Reports in the literature on bloom time over a 24-hour cycle are inconsistent. It was stated that the time of blooming is affected by darkness and temperature, but generally occurs between 10 pm and 8 am. However, cool nights with heavy dews in more temperate latitudes are associated with delayed flowering, from 8 am to 4 pm. The flower opens in about ten minutes, allowing the stigmas and anthers to emerge. Pollen may dehisce from the anthers immediately upon emergence or may delay shortly depending upon environmental conditions. The time between the opening and closing of the glumes ranges from half an hour to four hours, but averages about two hours. Cultivated sorghum panicles may produce up to 24 million grains of pollen, which is sensitive to desiccation and remains viable for only three to six hours. However, in one study, pollen kept at 4 °C and 75% relative humidity remained viable for 94 hours, and pollen stored in pollination bags in the shade in the field in Davis, California remained viable for over 20 hours. While stigmas can be receptive two days before and up to a week after flowering, the optimal time frame for pollination is within the first 72 hours. Pollen germinates immediately upon reaching a receptive stigma and fertilisation of the egg cell occurs about two hours later to initiate seed development. Cultivated sorghum is primarily self-pollinating; however, wind-mediated cross-pollination does occur. Insect pollination may also occur, based upon observations of honey bees, wild bees (sometimes known as solitary bees) and one species of beetle visiting several sorghum flowers consecutively. Upon collection of the insects, pollen grains identical to the grains collected from the sorghum anthers were found on all of the insects, with the honeybee carrying the most and the beetle carrying the least. However, no attempt was made to determine if insect movement resulted in cross-pollination (OECD, 2017).

S. bicolor is predominantly self-pollinating, but under specific conditions wind-mediated cross-pollination can occur over 60%, depending on the genotype, and average about 6%. As a result of self-pollination and out-crossing, most sorghum landraces grown by subsistence farmers are mixtures of inbred and partially inbred lines. The level of out-crossing varies and is influenced by the panicle type of the cultivar; typically out-crossing is higher in loose-panicled grassy sorghum and lower in compact-panicled domesticated sorghum. The estimated out-crossing rate in domesticated sorghum under field conditions ranges from 5% to over 40%. Several pollinator species have been observed consecutively visiting domesticated sorghum flowers. Upon insect collection, sorghum pollen grains were found on all of the insects. However, it was not determined if insect movement resulted in cross-pollination. More studies are needed to determine the extent of insect pollination in *S. Bicolor* (House 1985; Inspection, 2021). The flowering and pollination of *S. bicolor* is described in House (1985). Inflorescence development begins when a floral initial forms 30 to 40 days after germination. Domesticated sorghum normally flowers 55 to 70 days after germination in warm climates, but depending on the genotype, flowering may occur 30 to 100 days after germination. Wet and cool weather can also delay flowering. Flowers begin to open two days after the emergence of the inflorescence from the boot. Flowering starts in the sessile spikelets (multiflowered subdivisions of the inflorescence) at the tip of the inflorescence and progresses downwards over 4 to 5 days. A single panicle may have up to 6,000 florets. All heads do not flower at the same time in a field, so pollen is usually available for 10 to 15 days. Flowering time varies based on the genotype and climate, usually occurring from midnight to mid-morning and peaking around sunrise. The swelling of the lodicules facilitates flower-opening. When the stigma becomes visible, the stamen filaments elongate and the anthers become pendent. When the anthers are dry they dehisce and pollen is shed through the apical pore. Most pollen from a head fertilizes eggs on the same head. Cross-pollination can occur if pollen is blown into the air. The stigma is pollinated before the emergence of the anthers from the spikelets. Pollen grains drift to the stigma and germinate. A pollen tube develops with two nuclei and grows down the style to fertilize the egg. A sperm nucleus fertilizes the egg to form a 2*n* embryo and the other nucleus fuses with the polar nuclei to form a 3*n* endosperm. After pollination, the glumes close and the empty anthers and stigmas usually protrude. Some long-glumed varieties are cleistogamous (the florets do not open for fertilization). Unpollinated stigmas remain receptive for up to 16 days. After fertilization, organ differentiation occurs over approximately 12 days. Seeds pass through three development stages: milk, early dough, and late dough, and reach maturity after about 30 days. *S. bicolor* reproduces through seeds (Inspection, 2021).

Sorghum is considered as an often cross-pollinated species, with outcrossing up to 6 % depending on the genotype and growing conditions (Hariprasanna and Patil, 2015). The flowering occurs prior to sunrise and extended up to mid-day, the blooming starts from tip of the panicle in downward direction. The stigma is receptive before flowering and remains receptive for 6 to 8 days. Pollens are viable for few hours and fertilization is completed within 2 to 4 hours of pollination, jawar is normally self pollinated crop but stigmas exposed before dehisce lead to 6 to 30% cross pollination. The glumes open due to swelling of lodicules and another come out stigma. The stigma remains receptive for 8 to 16 days after blooming (Agriinfo, 2016). Pollination is done on next day between 9 to 10 a.m. all flower come to bloom. Inserting and shading the head in the bag collect the pollen. Another technique is clipping the heads early in the morning and placed in the boxes to flower in protected place. The collected pollens are dusted over exposed stigma or the pollen producing head brushed over emasculated head (Agriinfo, 2016). Sorghum is a self-pollinated crop with the natural cross-pollination from 0.6 to 15 % depending on the genotype, panicle type, and wind direction and velocity. The inflorescence is a raceme, consisting of one to several spikelets. The spikelets usually occur in pairs, one being sessile and the second borne on a short pedicel, except the terminal sessile spikelet, which is accompanied by two pedicelled spikelets. The sessile spikelet contains a perfect flower whereas the pedicillate spikelet possesses only anthers but occasionally has a rudimentary ovary and empty glumes (Kumar, 2016). In sorghum anthesis starts with the exsertion of the complete panicle from the boot leaf. Flowers begin to open two days after complete emergence of the panicle. The sorghum head begins to flower at its tip and anthesis proceeds successively downward. Anthesis takes place first in the sessile spikelets. It takes about 6 days for completion of anthesis in the panicle with maximum flowering at 3 or 4 days after anthesis begins. Anthesis takes place during the morning hours, and frequently occurs just before or just after sunrise, but may be delayed on cloudy damp mornings. Maximum flowering is observed between 06:00 and 09:00 h. Because all heads in a field do not flower at the same time, pollen is usually available for a period of 10–15 days. At the time of flowering (anthesis), the glumes open and all three anthers fall free, while the two stigmas protrude, each on a stiff style. The anthers dehisce when they are dry and pollen is blown into the air. Pollen in the anthers remains viable several hours after shedding. Flowers remain open for 30–90 min. Dehiscence of the anthers for pollen diffusion takes place through the apical pore. The pollen drifts to the stigma, where it germinates; the pollen tube, with two nuclei, grows down the style, to fertilize the egg and form a 2*n* nucleus. Stigmas get exposed before the anthers dehisce subjecting them to cross-pollination (Kumar, 2016). Pollination for crossing purposes should start soon after normal pollen shedding is completed during the morning hours. Sorghum is a breeder-friendly crop as it is amenable for crossing and selfing quite easily. For selfing, after panicle exsertion, bagging should be done by snipping off the flowered florets at the tip. Crossing is done by emasculation of selected panicles and dusting of pollen from identified plants. Hand emasculation is most commonly practiced in sorghum. Because of this ease in crossing, hybridization is most commonly followed in sorghum for trait improvement. For effective results in artificial hybridization the pollen is collected in pollen bags and thoroughly dusted on the emasculated or male-sterile panicles (Kumar, 2016). Sorghum bicolor is propagated through seeds produced by self-pollination, but out-crossing rates are in the range of less than 10% to 73% and to nearly 100% in individual Sudan grass plants. Wind is an important vector for significant rates of out-crossing and insects (honeybees, wild bees, beetles) may also contribute to cross pollination. Sorghum pollen is generally highly functional for about 30 minutes after the anthers dehisce, but its longevity is limited to two to four hours. Pollen kept under refrigeration is capable of fertilization for three to four days. Pollen viability and ability to germinate are influenced by temperature, humidity, and cloud cover. Stigmas are receptive for a day or two after blooming, but may remain receptive up to a week or more. The average number of sessile spikelets in a single inflorescence of sorghum is estimated by as 2000 to 4000 and each spikelet has 3 anthers with an average of 5000 pollen grains in each. The amount of pollen shed by anthers is a highly variable trait, depending on the genotype (Balakrishna and Bhat, 2016). Plants are primarily self-pollinated, but some wind pollination occurs. Cultivated sorghum is physiologically a perennial that is typically grown as an annual. In some environments a second ratoon (resprouted) crop is produced fom the unharvested roots and stolons of the first crop (OECD, 2017).

Crossing

Emasculation is done in 3 methods

1) In Hand Emasculation: Only the part of the peduncle is emasculated. Flowered tips and lower branches are removed by clipping. About 50 forets that would flower on next day are selected and emasculated and covered with suitable paper bag.

2) In Hot Water Method: The sorghum head is immersed in water at 450 to 48 0C for 10 minutes, without injury to the stigma.

3) In Plastic Bag Emasculation: Sorghum heads are covered with plastic bag ton create high humidity in side the bag. Under high humidity forets open, anther emerges, but shed no pollens and the anther removed easily by tapping (Agriinfo, 2016).

Enlarged spikelet and spikelets in two views are given in Fig. 13, 14.

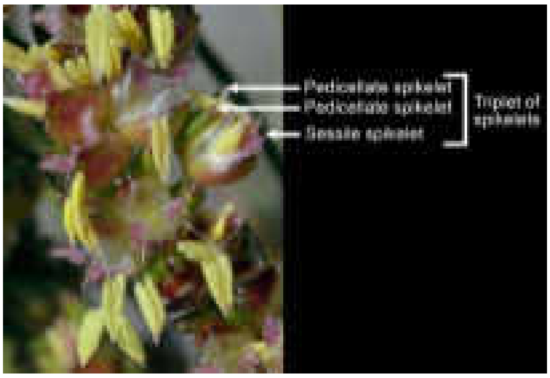


Fig. 13. Spikelets of cultivated sorghum. Sorghum has sessile and pedicellate spikelets. The sessile spikelets are bisexual (male and female), whereas the pedicellate spikelets may be male or sterile. Notice the feathery purple stigmas and the yellow anthers on the bisexual florets

Fig.14. Sorghum spikelets in two views. Sorghum has sessile and pedicellate spikelets. The sessile spikelets are bisexual (male and female), whereas the pedicellate spikelets may be male or sterile. In this example, the anthers appear to have been lost, probably because the fruits are relatively mature

GENETICS AND CYTOGENETIOCS

S. bicolor is a genetically diverse diploid (2n = 2x = 20). The classification of *S. bicolor* has been controversial and challenging due to high variability within the species. Snowdon (1936) defined a complex with annual members of *Sorghum* Moench subg. *Sorghum* comprising 7 weedy, 13 wild, and 28 cultivated species. All of these species, in addition to perennial members, were later grouped within the single species, *S. bicolor*. In the peer-reviewed literature and sources of grower information (seed companies, extension publications) terminology use is inconsistent and it is often challenging to determine the species, subspecies, and race or working group being referenced (Inspection, 2021). Sorghum is the C4 food crop for which complete genome sequence available and the complete genome sequencing of sorghum genotype Btx 623 estimated the genome size as 730 Mb and the GC content is estimated at 37.7%. In sorghum heterochromatin occupies at least 460 Mb and 252 Mb is euchromatin. The sorghum genome contains 55% retrotransposons, 7.5% of DNA transposons and 1.7% of miniature inverted-repeat transposable elements. Approximately 27,640 protein coding genes found in sorghum followed by 5,197 genes contain less than 150 amino acids have few exons and 727 processed pseudogenes. A total of 67 known micro RNAs (miRNAs) and 82 additional miRNAs identified in sorghum genome. Cytogenetic maps of sorghum chromosomes were constructed on the basis of the fluorescence in situ hybridization (FISH) using BACs. BTx623 an elite inbred line was used to estimate the molecular size of the each chromosome and established a generally accepted size based nomenclature for sorghum chromosomes (SBI-01 to SBI-10) and linkage groups (LG-01 to LG-10) (Kim et al., 2005a; Kim et al., 2005b). Extensive efforts in crop improvement have resulted in the development of a number of high-yielding cultivars with substantial yield increment over the years. The discovery and utilisation of the male sterility system have led to the successful commercial exploitation of heterosis. A number of biotic and abiotic yield-limiting factors and changes in consumption pattern and demand have resulted in a steady decline in cultivated area and grain production over the years. Much progress has been achieved in the field of sorghum biotechnology, including genomics over the last two decades. Adoption of genomic tools and molecular breeding strategies can help in tailoring sorghum cultivars with desired traits to enhance the productivity under various limiting factors in the years to come (Hariprasanna and Patil, 2015). Sorghum is a self-pollinating, diploid ($2n = 2x = 20$) species belonging to the Poaceae family with a genome size of 730 Mb, about 25 % the size of maize (Kumar, 2016). Most of the cultivated sorghum varieties and land races belong to *S. bicolor* subsp. *bicolor* of the Eu-Sorghum sub generic section of the *Sorghum* genus and other four, *Chaetosorghum*, *Heterosorghum*, *Parasorghum* and *Stiposorghum* contain 19, wild species native to Africa, Asia and Australia. The *S.bicolor* is diploid (2n = 20), Chaetosorghum and Heterosorghum contain the tetraploid (2n = 40). The ploidy varies in Parasorghum from 2n = 10 to 2n = 40 and most of species in Stiposorghum are diploid with 2n = 10, while *S. interjectum* has 2n = 30, 40 and *S. plumosum* has 2n = 10, 20, 30 (Balakrishna and Bhat, 2016). Sorghum is an interesting genus having a large number of well-recognized species taxonomically classified into five subgenera. Cytogenetic analysis led to the understanding of the nature of chromosomal variations, origins, and probable relationships based on chromosome morphology. Progress in the science of conventional and molecular cytogenetics, and genomic research provide a detailed insight into the genome organization of an individual or species, leading to enhanced utilization of genetic and physical information towards improvement of the crop. The integration of genetic, physical, and cytomolecular maps of the *Sorghum* genus is useful to scientists working on genomics of grass species. Large-scale molecular karyotyping of grass genomes would facilitate alignment of related chromosomal regions among different grass species and also facilitate genetic and cytogenetic studies of chromosome organization and evolution. As compared to other crop species little is known about the karyomorphology in sorghum mainly due to the small size of its chromosomes (Rakshit *et al.*, 2016). Cultivated sorghum is a genetically diverse diploid (2n = 2x = 20) with 200 classified phenotypic, genotypic and cytogenetic trait genes. It is sexually compatible with some of its wild or weedy relatives, and the level of cross-compatibility determines its primary and secondary gene pools. The primary gene pool lies within section Eusorghum and includes the other diploid species *S. propinquum*, *S. bicolor* subsp. *verticilliflorum*, and shattercane. Crosses within this gene pool are fully interfertile. The high level of fertility and spontaneous outcrossing of the primary gene pool leads to frequent introgression when distributions overlap and conditions are favourable. The secondary gene pool consists of the tetraploid (2n = 4x = 40) members of Eusorghum: Columbus grass (*Sorghum almum* Parodi) and Johnson grass. Domesticated sorghum is capable of out-crossing with members of the secondary gene pool despite ploidy level differences, producing either sterile triploids or somewhat fertile tetraploids. The tertiary gene pool includes species from other sections of sorghum. Outcrossing of cultivated sorghum with members of this gene pool is highly unlikely under natural conditions, and crosses produced through human intervention are anomalous, lethal or almost completely sterile. The cultivated sorghum genome has been sequenced. The haploid genome size is approximately 730 Mega base pairs (Mbp), larger than both Arabidopsis and rice (155 Mbp and 510 Mbp, respectively) (OECD, 2017). Sorghum is a predominantly self-pollinated diploid species with $2n = 2× = 20$ chromosomes. It has a small genome relative to other cereal crops, which is about 730 Mbp. Its whole genome was sequenced and made accessible for public use, which facilitated the development of DNA markers, such as single nucleotide polymorphism (SNPs) for various applications, including analyses of population genetics and identification of genomic regions associated with complex traits through quantitative trait loci (QTL) and association mapping (Enyew *et al.*, 2021). In the present study, population genomics analyses were performed on a worldwide collection of 445 sorghum accessions, covering wild sorghum and four end-use subpopulations with diverse agronomic traits. Frequent genetic exchanges were found among various subpopulations, and strong selective sweeps affected 14.68% (~1075 Mb) of the sorghum genome, including 3649, 4287, and 3888 genes during sorghum domestication, improvement of grain sorghum, and improvement of sweet sorghum, respectively. Eight different models of haplotype changes in domestication genes from wild sorghum to landraces and improved sorghum were observed, and *Sh1*-and *SbTB1*-type genes were representative of two prominent models, one of soft selection or multiple origins and one of hard selection or an early single domestication event. We also demonstrated that the *Dry* gene, which regulates stem juiciness, was unconsciously selected during the improvement of grain sorghum. Taken together, these findings provide new genomic insights into sorghum domestication and breeding selection, and will facilitate further dissection of the domestication and molecular breeding of sorghum (Wu *et al.*, 2022). Genomics has made rapid advances during the past decade. The sorghum genome has been sequenced, and important gene transcripts and regulatory mechanisms are being deciphered on a large scale worldwide (Prabhakar *et al.*, 2022). The genome of *S. bicolor* was sequenced. It is generally considered diploid and contains 20 chromosomes, however, there is evidence to suggest a tetraploid origin for *S. bicolor*. The genome size is approximately 800 Mbp (Wikipedia, 2023).

GENETIC DIVERSITY

Genetic diversity is the base for survival of plants in nature and for crop improvement. Diversity in plant genetic resources provides opportunity for plant breeders to develop new and improved cultivars with desirable characteristics, which include both farmer-preferred traits (high yield potential, large seed) and breeder-preferred traits (pest and disease resistance and photosensitivity). From the very beginning of agriculture, natural genetic variability has been exploited within crop species to meet subsistence food requirement. Later the focus shifted to grow surplus food for growing populations. Presently the focus is on both yield and quality aspects of major food crops to provide balanced diet to human beings (Bhandari *et al.*, 2017). Genetic diversity facilitates breeders to develop varieties for specific traits like quality improvement and tolerance to biotic and abiotic stresses. It also facilitates development of new lines for non-conventional uses like varieties for biofuel in sorghum, maize etc. Diversity is also important with respect to adaptability of crop plants to varied environments with special reference to changing climatic conditions (Bhandari *et al.*, 2017). Sorghum is believed to have a wide range of diverse germplasm. Plant genetic resources play an important role in generating new high yielding crop varieties with desired traits. Characterization and identification of sorghum genotypes conferring important traits for genetic improvement is a prerequisite in plant breeding activities. Kimber *et al* (2013) presented details of the major world sorghum collections and breeding lines that total over 150,000 accessions. Sorghum improvement deals with production of new crop cultivars that are superior to existing cultivars for traits of interest. Availability of genetic variability for these traits, knowledge about their heritability and inheritance, and availability of effective phenotyping methodologies are fundamental for success of any crop improvement program. In fact, the efficiency of phenotyping and its robustness decides the success of the crop improvement program in terms of producing a tangible product or technology (Kumar, 2016). Studying the genetic diversity of a crop is very important for effective germplasm management, utilization, and genotype selection for crop improvement. It is the most important step for conserving and increasing the rate of genetic gain in crop-breeding programs. The level of genetic diversity within a species is commonly used to measure the level of species adaptability and survival in unpredictable environmental conditions. Similarly, the level of genetic variation within a population is the basis for germplasm selection in plant breeding and is vital for crop improvement. Hence, the conservation and utilization of plant genetic variation are crucial to human food security (Enyew *et al.*, 2021). The genetic diversity in sorghum provides an opportunity to search for new genes and alleles that are responsible for conferring desirable phenotypes. Genome profiling using molecular markers would provide a large number of DNA markers. Genomic selection programs would pave way for effective utilization of sorghum germplasm for crop improvement (Prabhakar *et al.*,2022).

Sorghum seed or grain is a caryopsis fruit about 3-4 mm in diameter, spherical and oblong in shape and black, red and yellow in color (Botanical,2023). The seeds of Sorghum vary widely among different types in colour, shape, and size, but they are smaller than those of wheat. Sorghum grains are of different colors: white, brown, red, yellow, lemon yellow, cream, and black (Fig. 15) (Britannica, 2023). Sorghum panicles can range from very tight and compacted to spreading with long branches (Fig. 16) (GD,2023).

Fig. 15. Genetic variability for seed color, size and shape of Sorghum

Fig. 16: Variability for compactness of Sorghum panicle

During 1960s Rockefeller Foundation with Indian Agricultural Research Program collected a total of 16,138 accessions from different countries and International Sorghum (IS) numbers were assigned to them. At present, ICRISAT is a major repository for the world sorghum germplasm collection with a total of 36,774 accessions from 90 countries. The existing collections of sorghum germplasm conserved at ICRISAT have been estimated to represent about 80% of the variability present in the crop. About 90% of these collections have come from developing countries in the semi-arid tropics. About 60% of these collections have come from six countries: India, Ethiopia, Sudan, Cameroon, Swaziland, and Yemen. The largest collection is from India. In addition to this, the germplasm maintained at ICRISAT, India, are classified into five races: bicolor, guinea, caudatum, kafir and durra and their derivative (Gopal Reddy *et al*.,2002; Balakrishna and Bhat, 2016).

Sorghum is the important cereal crop around the world and hence understanding and utilizing the genetic variation in sorghum accessions are essential for improving the crop. A good understanding of genetic variability among the accessions will enable precision breeding. So profiling the genetic diversity of sorghum is imminent. In the present investigation, forty sorghum accessions consisting of sweet sorghum, grain sorghum, forage sorghum, mutant lines, maintainer lines, and restorer lines were screened for genetic diversity using quantitative traits. Observations were recorded on 14 quantitative traits, out of which 9 diverse traits contributing to maximum variability were selected for genetic diversity analysis. The principle component analysis revealed that the panicle width, stem girth, and leaf breadth contributed maximum towards divergence. By using hierarchical cluster analysis, the 40 accessions were grouped under 6 clusters. Cluster I contained maximum number of accessions and cluster VI contained the minimum. The maximum intercluster distance was observed between cluster VI and cluster IV. Cluster III had the highest mean value for hundred-seed weight and yield. Hence the selection of parents must be based on the wider intercluster distance and superior mean performance for yield and yield components. Thus in the present investigation quantitative data were able to reveal the existence of a wide genetic diversity among the sorghum accessions used providing scope for further genetic improvement (Sweta Sinha and Kumaravadivel, 2016).

The aim of this study was to evaluate the level of genetic diversity within and among sorghum germplasms collected from diverse institutes in Nigeria and Mali using Single Nucleotide Polymorphic markers. Genetic diversity among the germplasm was low with an average polymorphism information content value of 0.24. Analysis of Molecular Variation revealed 6% variation among germplasm and 94% within germplasms. Dendrogram revealed three groups of clustering which indicate variations within the germplasms. Private alleles identified in the sorghum accessions from National Center for Genetic Resources and Biotechnology, Ibadan, Nigeria and International Crop Research Institute for the Semi-Arid Tropics, Kano, Nigeria shows their prospect for sorghum improvement and discovery of new agronomic traits. The presence of private alleles and genetic variation within the germplasms indicates that the accessions are valuable resources for future breeding programs (Afolayan *et al*.,2019). Sorghum is a drought-tolerant staple crop for half a billion people in Africa and Asia, an important source of animal feed throughout the world and a biofuel feedstock of growing importance. Cultivated sorghum and its inter-fertile wild relatives constitute the primary gene pool for sorghum. Understanding and characterizing the diversity within this valuable resource is fundamental for its effective utilization in crop improvement. Here, we report analysis of a sorghum pan-genome to explore genetic diversity within the sorghum primary gene pool. We assembled 13 genomes representing cultivated sorghum and its wild relatives, and integrated them with 3 other published genomes to generate a pan-genome of 44,079 gene families with 222.6 Mb of new sequence identified. The pan-genome displays substantial gene-content variation, with 64% of gene families showing presence/absence variation among genomes. Comparisons between core genes and dispensable genes suggest that dispensable genes are important for sorghum adaptation. Extensive genetic variation was uncovered within the pan-genome, and the distribution of these variations was influenced by variation of recombination rate and transposable element content across the genome. We identified presence/absence variants that were under selection during sorghum domestication and improvement, and demonstrated that such variation had important phenotypic outcomes that could contribute to crop improvement. The constructed sorghum pan-genome represents an important resource for sorghum improvement and gene discovery (Yongfu Tao *et al*.,2021). This study aimed to investigate the genetic diversity of Ethiopian sorghum using gene-based single nucleotide polymorphism (SNP) markers. In total, 359 individuals representing 24 landrace accessions were genotyped using 3,001 SNP markers. The SNP markers had moderately high polymorphism information content (PIC = 0.24) and gene diversity (H = 0.29), on average. This study revealed 48 SNP loci that were significantly deviated from Hardy–Weinberg equilibrium with excess heterozygosity and 13 loci presumed to be under selection ($P < 0.01$). The analysis of molecular variance (AMOVA) determined that 35.5% of the total variation occurred within and 64.5% among the accessions. Similarly, significant differentiations were observed among geographic regions and peduncle shape-based groups. In the latter case, accessions with bent peduncles had higher genetic variation than those with erect peduncles. More alleles that are private were found in the eastern region than in the other regions of the country, suggesting a good *in situ* conservation status in the east. Cluster, principal coordinates (PCoA), and STRUCTURE analyses revealed distinct accession clusters. Hence, cross breeding genotypes from different clusters and evaluating their progenies for desirable traits is advantageous. The exceptionally high heterozygosity observed in accession *SB4* and *SB21* from the western geographic region is an intriguing finding of this study, which merits further investigation (Enyew *et al.,* 2021).

BREEDING

Germplasm

The major organisations/countries which maintain sorghum genetic resources are the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India, the National Plant Germplasm System (NPGS) in United States, Ethiopia, Sudan, South Africa, India and China, primarily because of the large crop improvement programmes (Reddy, 2017). The International Crops Research Institute for Semiarid Tropics (ICRISAT) at Hyderabad, India is the major germplasm collection centre and serve to disseminate sorghum accessions all over the world. The National Centre for Sorghum at Hyderabad in India and one at Ahmadu Bello University, Zaria, Nigeria are the national germplasm repositories (Pallavi, 2023).

Breeding Objective (Agriinfo, 2016):

1) High grain and fodder yield.
2) Early maturity
3) Resistance to drought, low HCN content, leafy, sweet juicy fodder.
4) Resistance to disease - Blight, downy mildew, rust, smut, charcoal, etc.
5) Resistance to insect pests - Midge, stem borer and shoot fly, etc
6) Bread making quality.

Breeding Methods: The crop improvement methods depend on the pollination control mechanisms and cultivar options. As mentioned earlier, sorghum is a breeder-fiendly crop. One can employ the breeding methods that can be used to improve both self- and cross-pollinated crops with ease in sorghum. This is the reason why one can find sorghum pure line varieties, hybrids, and populations as cultivar options in different parts of the world. However, sorghum hybrids are superior to pure lines and populations for yield and other important agronomic traits. The discovery of cytoplasmic-nuclear male sterility in sorghum helped to produce hybrid seeds on a mass scale using a three-line system (A, B, and R) for commercial cultivation of hybrids (Kumar, 2016).

Pure Line Selection: In this method superior land races are selected from local uniform variety and grown as plant progenies in the next year. Uniform superior progenies harvested and bulked as improved strain for further evaluation. In varietal evaluation, if improved strain shows superiority over the existing variety , it is released for commercial cultivation on large scale. *e.g.,* 1) M-35-1, 2) Sd-3, 3) Yashda , 4) Maulee(RSLG-262) (Agriinfo, 2016). Pure line selection is the most common method of crop breeding particularly in self-polinated crops. Pure line selection is practiced under two situations: (i) when there is a need to develop a variety from a landrace population, and (ii) while developing a variety from a segregating population. For example, in sorghum, for post-rainy season adaptation in India, the local landraces from the state of Maharashtra were collected and single plant selections were made for a couple of generations and the performance for grain and stover yields of the selected lines was compared. The line showing better performance than the check variety for yield traits across locations was released for commercial cultivation. In the case of segregating populations, the individual plants are heterozygous in the beginning as they are the products of crossing between two homozygotes and attain homozygosity in successive generations upon self-pollination. Individual plant selections have to be carried out for at least five to six generations to achieve the desired level of homozygosity of a pure line. A higher number of plants (3000–10,000) of segregating population are evaluated and selection is practiced to obtain the desired plants (Kumar, 2016).

Pedigree Method: This method consists of hybridization between desirable complementary parental lines, followed by selection of superior plants, in the segregating generation, till homozygosity is achieved. *i.e.,* F5-F6. The selected plants are bagged to prevent out crossing varieties developed by pedigree method are SPV-86 (R-24 X R-16), SPV-504 (Swati) (SPV 86 X M-35-1), CSV-15 R, (SPV-475 X SPV-462) (Agriinfo, 2016).

Back Cross Breeding: It is used to transfer one or few inherited traits from donor to another desirable genotype (recipient parent) resistance to disease like grain mold, downy mildew, rust, smut, and resistance to insect pest like midge, shoot fly, stem borer could be introduced in desirable strain by back cross breeding. Similarly cytoplasmic genetic male sterility could also be introduced by this method (Agriinfo, 2016).

Hybrid Breeding: Seeds of hybrid sorghum are produced using cytoplasmic genetic male sterility typically known as A, B and R line system. Kambine Kafir - 60 (m.s) was initial m.s line is used in hybrid seed production. Male sterile line is known as A line its maintainer is known as B line. Line A and B are isogenic except that line A is male sterile line and B is male fertile. The difference lines only in cytoplasm, where line A has sterile cytoplasm and line B has fertile cytoplasm. Any fertile line can be converted into male sterile by backcross breeding method (Agriinfo, 2016).

Maintaince of A, B and R Lines: A planting A and B line in 4:2 ratios in isolated field Maintaince male sterile line A. Seed produced on A line is male sterile. Line B is self fertile growing crop isolation or bagging the heads of B line plants, maintains B line. Similarly line R is also self fertile, is also multiplied by planting in isolated field. In commercial seed production, i.e bulk production of A, B and R line is referred as foundation seed production and production of A X R referred as certified seed production.

A Line (msms) X B Line (msms) = A line (msms)

Male Sterile X Male Fertile = Male Sterile
A Line (msms) X R Line (MsMs) = (Msms) Hybrid Seed
Male sterile X Male Fertile = Male Fertile

New hybrids can be developed by improving performance of 'A' and 'R' lines or both by the back cross breeding method. Every year crossing programme of restorers with promising male sterile lines is undertaken and hybrids are tested for performance. If performance of particular hybrid found superior, it is multiplied on large scale for commercial cultivation. The popular hybrids are CSH-1, CSH-5, CSH-12, CSH-15 and CSH-16 (Agriinfo, 2016).

Hybridization-Based Methods: The term hybridization refers to the crossing of two genetically different individuals as it com- bines the traits of two varieties and provides an opportunity to select plants with desirable features of both parents through recombination in the segregating progeny. As the natural variability for most traits is limited or already exploited, there is a need to create new variability by making artificial hybrids to make any further dent in developing improved varieties through selection in the segregating populations. As most of the traits of interest in sorghum are quantitatively inherited, sorghum breeders generally use the pedigree method of selection in segregating populations. In the pedigree method, the records of the ancestry or pedigree of each progeny is maintained and it is easy to trace back the parentage and selection. With the pedigree sys- tem, the F_2 generation represents the *first* and the maximum opportunity for selection. Selection for superiority is based on the vigor and other agronomic features of progeny (families). In F_2, selection is limited to individuals. In F_3 and subsequent generations, until a reasonable level of genetic homozygosity is reached, selection is practiced both within and between families. Of the >700 sorghum female parents (A-/B-pairs) developed by ICRISAT for various traits of global importance, more than 600 parents are used in crossing to develop them using the pedigree method (Kumar, 2016). Population improvement is another important method for sorghum improvement, which includes: (i) the development of broad genetic-based gene pools, and (ii) its improvement through recurrent selection methods. In sorghum a single gene in recessive homozygous condition confers male sterility and eight differ- ent genes reported in sorghum are involved in control of genetic male sterility. Using these genes, population improvement methods can be successfully deployed in sorghum which pro-vides a long-term breeding strategy to derive diverse and broad genetic-based superior varieties/hybrid parents. More than 50 sorghum hybrid parents (A-/ B-pairs) at ICRISAT were developed using population improvement methods (Kumar, 2016).

Heterosis breeding is most important as hybrids are the cultivar options in sorghum wherever they are available. Although heterosis was demonstrated as early as 1927 in sorghum, its commercial exploitation was possible only after the discovery of a stable and heritable cytoplasmic-nuclear male sterility (CMS) mechanism (Kumar, 2016). In sorghum, commercial exploitation of heterosis has been possible owing to availability of a stable and heritable CMS mechanism enabling large-scale, economic hybrid seed production and sufficiently high magnitude of heterosis across a range of production environments for economic characters. The greater contribution of hybrids to yield, compared to improved and landrace varieties, has been demonstrated in almost every situation/condition. The hybrids besides being superior for grain yield and other traits of interest are stable across environments. In India, many improved high yielding hybrids and varieties of *kharif, rabi*, forage, and sweet sorghum, suitable to different zones/states, have been released for cultivation, which resulted in higher production and productivity (Prabhakar *et al*.,2022).

Mass Selection: Mass selection differs from pure line selection, wherein a number of desirable plants (instead of only one) are selected and compositing is done on the harvested seed to produce the next generation. This method has a few drawbacks. It is not known whether the plants being grouped are homogeneous and some of them if heterogeneous would segregate further in following generations, and repeated selection would be required. Mass selection is generally practiced to purify a variety. A large number of single plants are selected from an impure variety population, each line progeny tested, and similar type progeny bulked to form the pure seed lot. The success of the method depends upon high heritability, that is, the presence of additive gene action and minimal influence of genotype environment interaction on the expression of the selected trait. Mass selection is relatively less used in sorghum except for the improvement of plant height or grain size (Kumar, 2016).

Breeding for nutrition content: Quality sorghum grain is usually hard (vitreous), white with a pearly luster, bold and round, with a thin seed coat (pericarp), and without a colored subcoat (testa). However, there are many variations in color, hardness, and shape of the grain used for food in different parts of tile world. The quality of sorghum protein is deficient, like that of several other cereal crops, because of a low concentration of the essential amino acid, lysine. High-lysine sorghum types have been found growing In the wollo have district of Ethiopia, and several other sources now been Identified. Breeding programs are actively studying the possibility of Incorporating this trait into their better lines and varieties for farmer use. Many problems are involved, probably limiting high-lysine sorghum to special uses (House, 1985).

Resistance Breeding: The resistance could be incorporated in given strain when desirable donor present is available by back cross breeding. Effective identification of donor and screening technique of mode of inheritance in needed, the characters controlled by recessive gene could easily be transferred by back cross breeding than character controlled by dominant genes. The important resistance source for pest and disease are given below (Agriinfo, 2016).

Biotechnology: Trait-based approach for the genetic improvement of sorghum has been adopted by use of cutting-edge technologies of plant biotechnology and molecular biology to develop genotypes with improved performance under stress during crop growth and enhanced quality of the produce with extended shelf life of seed, grain, and novel sorghum products (Prabhakar *et al*.,2022). Plant biotechnology is increasingly used for *S. bicolor* improvement with the application of molecular genetics, genomics, and plant transformation. Transgenic traits have been added to *S. bicolor* using *Agrobacterium*-mediated transformation and particle bombardment. *S. bicolor* has been highly recalcitrant to genetic transformation and until recently the transformation efficiency was less than 10% (Inspection, 2021).

Breeding

Most improvements to *S. bicolor* have been achieved using conventional breeding. Conventional sorghum breeding methods include germplasm evaluation and enhancement, backcrossing, pedigree selection, recurrent selection and hybrid development using cytoplasmic and genetic male sterility. Limited genetic variation is found in sorghums in many locations (*i.e.,* the germplasm base is narrow), so crosses between, or selection from collections made within the same area usually result in minimal yield increase. To increase desirable traits, collections from other breeding programs, and breeding procedures including the formation of composites, which retain more variability are often used. One major crop improvement was the introduction of chemically induced brown midrib mutants that have less lignin in the stalk and, therefore, have improved fibre digestibility (House 1985; Inspection, 2021).

Sorghum is predominantly self-pollinated crop, in which cross-pollination ranges from 5% to 15% with an average of about 6%. Thus, breeding procedures applicable to both self- and cross-pollinated crops can be deployed to sorghum improvement. Defining breeding goals is must for any plant breeder before start of the work. In case of sorghum breeding, first, the breeder needs to understand the requirements of the farmers, the millers, the bakers, the target environments, including the level of biotic and abiotic stresses, consumer preference, the processing industry, and the production practices of the farmers. Goals of sorghum breeding always revolve around yield and yield stability, resistance to diseases and pests, tolerance/resistance to drought, salinity and high-temperature stresses, reduction in antinutritional factors, improving the grain protein quality, identifying particular genotypes to specific end uses, earliness, photo- and thermo-insensitivity, wider adaptability, high biomass, high sugar content, and several agronomic trait improvements. Choice of breeding methodology in sorghum depends on the type of cultivar (varieties/hybrids) intended to be developed. In the development of lines and varieties in often cross pollinated crop like sorghum, breeding procedures applicable to self pollinated crops are followed. However, as it allows cross-pollination to some extent, availability of male sterility sources made it easy for breeder to exploit heterosis in the form of hybrids. In this chapter different conventional and selection procedures, which are commonly used in sorghum improvement, are represented with detailed discussion and schematic representation (Rakshit and Bellundagi, 2019.).

The major milestones in sorghum breeding in India

- Diversification of genetic base of cultivars using exotic germplasm.
- Development of hybrid parents and release of hybrids to exploit heterosis for grain, fodder and biomass yields.
- Population improvement approach to augment the breeding material with desirable traits and alleles.

Sorghum is one of the first crops in which heterosis could be beneficially exploited in India. Commercial exploitation of heterosis has been possible owing to the availability of a stable and heritable CMS mechanism, enabling large-scale, economic hybrid seed production and high magnitude of heterosis for economic traits. The hybrid programme in India was initiated in early 60s by attempting crosses of Indian tall cultivars as well as temperate dwarf parents as male parents on exotic CMS lines (CSH 1 to 4). With the breeding efforts in the Indian sorghum improvement program, improved and promising parental lines became available and were used to develop future set of hybrids (CSH 6onwards) after 1975. From CSH 13 to the latest hybrid CSH 30, diversification of hybrids became a priority and traits such as earliness, grain size and mold tolerance were incorporated in new hybrids. The multi-cut forage sorghum hybrid CSH 24MF provides for the highest forage yield (91ton fresh forage/ha) coupled with superior forage quality (8% protein and 50% digestibility). Sweet sorghum cultivars with high stem sugar content were also identified and released. Notable ones are the varieties such as SSV 84 (high brix), CSV 24SS (High stalk and sugar yields) and hybrid CSH 22 SS (High stalk and sugar yields) (Balakrishna and Bhat, 2016).

Advancements and Challenges

Breeding efforts of nearly 50 years have catapulted the yields of sorghum by many folds for both grain and fodder use. However, challenges remain in the areas of improving resistance to biotic and abiotic stresses, significant improvement in terms of nutritional quality, bioavailability, and consumer acceptability. For the past several decades, several programs in India attempted to improve varieties and/or hybrid parents through pedigree breeding approach. More dramatic accruals in terms of grain yield and fodder/ biomass yield came through in the initial years and have reached a plateau thereafter. While the increase in productivity was possible by introgressing exotic material in *kharif* grain sorghum types, it resulted in greater susceptibility of the cultivars thus developed to biotic stresses and loss of consumer preference, in many instances. While complete immunity against major pests and diseases are not available, there is enough scope to build fair level of tolerance against most of these pests and diseases by conventional breeding and high resistance against grain mold and major pests by biotechnological approach and gene pyramiding. Genetic resistance in conjunction with other components of integrated plant protection management could offer lasting low cost solutions. Increments in productivity were much slower in rabi-adapted cultivars compared to kharif-adapted ones (Kumar *et al.,* 2010). Temperate photo-insensitive germplasm could not help development of rabi (post-rainy) cultivars of grain sorghum adapted to receding moisture conditions where local varieties (such as M35-1 that was released in 1937) are largely cultivated (Reddy *et al.,* 2008; Rakshit *et al.*, 2012).

The advanced breeding programmes in forage breeding using diverse germplasm lines has resulted in more than doubling of forage yields in hybrids compared to varieties. However, absence of heterosis for biomass production had limited the progress in enhancement of forage yields of late. There is no easy answer to enhance forage production potential other than looking at diverse genetic backgrounds to yield more biomass or generate high heterosis for forage yield traits. The only sweet sorghum hybrid CSH 22 SS released in the country is the bench mark for sweet sorghum productivity. There is a need to develop newer cultivars that produce high stalk yield and more energy in different agro-climatic areas of the country. They should also possess resistance/tolerance to various stresses and should be of staggered maturity times to widen the harvest window, ensuring continuous supply of feed stock to the sweet sorghum processing plants. Any increase in biomass resulting from these breeding programmes would also ensure an important role for sweet sorghum as both first and second generation biofuel (Balakrishna and Bhat, 2016).

Major Types of Sorghum

Grain Sorghum: Grain sorghum can take many shapes and sizes from a tight-headed, round panicle to an open, droopy panicle that can be short or tall. Grain sorghum comes in red, orange, bronze, tan, white, and black varieties. Red, orange or bronze sorghum are very versatile and can be used in all segments of the sorghum industry. Tan, cream and white colored sorghum varieties are typically made into flour for the food industry. Black and burgundy varieties contain beneficial antioxidant properties and are used in other food applications.

Forage Sorghum: Depending on which species and variety is selected, sorghum can be used for grazing pasture, hay production, silage and green-chop. Forage sorghum typically grows 8-15 feet tall and is most popular for use as silage for feeding livestock.

Biomass Sorghum: Did you know sorghum can be used to make ethanol? Biomass sorghum has the largest stature of all the sorghum varieties, reaching a height of 20 feet in a normal growing season. Biomass sorghum has been bred to produce a large amount of non-grain biomass. These hybrids are used primarily for the production of bioenergy.

Sweet Sorghum: Sweet sorghum is predominantly grown for sorghum syrup. Unlike grain sorghum, sweet sorghum is harvested for the stalks rather than the grain and is crushed like sugarcane or beets to produce a syrup. Sweet sorghum was once the predominate table sweetener in the

U.S. Today, sweet sorghum is used as a healthy alternative sweetener to produce whiskey and rum type products and for biofuel and chemical production.

Types of Sorghum (Plantvillage, 2023).
Sorghum is a versatile crop that comes in many different varieties, each with its own unique characteristics and uses.
Grain sorghum, also known as milo, is the most widely grown type and is used for food, animal feed, and biofuel production.

Sweet sorghum has a high sugar content and is used for the production of sorghum syrup, molasses, and other sweeteners.

Forage sorghum, which is primarily used for animal feed, is harvested for its leaves and stalks rather than its grain.
Broomcorn sorghum grown for the production of brooms and brushes, which are made from the plant's long, stiff fibers.

Dual-purpose sorghum, as the name suggests, is grown for both grain and forage and is used to feed both humans and animals.

High-tannin sorghum, on the other hand, is grown for its high tannin content, which makes it resistant to bird and insect damage.

There are many specialty varieties of sorghum that are grown for specific uses, such as **ornamental purposes, traditional medicine,** and **cultural practices.**

Harvesting (Plantvillage, 2023).
The harvesting procedure for sorghum can vary depending on the specific variety, climate, and soil conditions. However, there are some general steps that can help ensure a successful and efficient harvest:
Determine maturity: Sorghum should be harvested when it reaches physiological maturity, which is when the seed head turns from green to yellow, brown, or red and the seeds become hard and difficult to dent.
Timing: The timing of the harvest will depend on the climate and variety, but generally, sorghum is harvested during the dry season, when the seeds have matured and dried out.

Equipment: Use appropriate equipment, such as a combine harvester or sickle, to harvest the sorghum.

Cutting: Use a sickle or combine harvester to cut the stalks near the base of the plant. The stalks can be cut at a height of 10-15 cm above the ground to leave some stubble for erosion control and soil conservation.
Drying: Allow the sorghum to dry in the field for a few days to a week to reduce moisture content and improves torage quality.

Threshing: Use a thresher or other equipment to remove the seeds from the seed head. Alternatively, the seed heads can be beaten with a stick to release the seeds.

Varieties

Hybrids and varieties released through AICRP at National Level are given in Table 8.

Table 8. Hybrids and varieties released through AICRP at National Level

	Hybrid		Centre	Recommended for the states of	Remarks
	CSH 26		Dev Gen Seeds	Maharashtra , Karnataka, MP, South Gujarat, and north AP & TN	Kharif Hybrid, 205 cm ht, White midrib colour, semi erect leaves, semi compact panicle. Tolerant to Charcoal rot, Ergot, Rust, shoot fly, aphids and stem borer.
	CSH 27		ICAR-IIMR	Rajasthan, North Gujarat, UP, AP and Tamil Nadu	Kharif Hybrid, 205 cm ht, Tan plant color with cylindrical semi compact panicle and white bold elliptical seed. Medium maturity group. Tolerant to grain mould disease under natural conditions
	CSH 28		Nuzveedu seeds	Maharashtra , Karnataka, MP, South Gujarat, and north AP (Zone II)	Kharif Hybrid, 203 cms, medium tall, Medium Maturity , Long bold panicle, bold grains, tolarent to shoot fly and grain mold. High grain and fodder yields, high response to nitrogen fertilizer.
	CSH 29		Mahodaya Seeds	Maharashtra , Karnataka, MP, South Gujarat, and north AP (Zone II)	Kharif Hybrid, 220 Cm tall, White midrib colour, semi erect leaves, semi compact panicle, lustrous grain, Medium maturity, Resistant to foliar diseases, moderately resistant to grain mold.
	CSH 30		ICAR-IIMR	Maharashtra, Karnataka, MP, South Gujarat, North AP under rainfed Kharif cultivation	Resistant to lodging. Non-shattering. Tan, 216 cm tall, plant color with symmetric semi compact panicle and white bold elliptical seed.
	CSH 31R		Dev Gen seeds	All rabi sorghum growing states of India	Rabi hybrid with high grain yield and fodder yield. Tolerant to drought.
	CSH 32		Dev Gen seeds	Maharashtra , Karnataka, MP, South Gujarat, and north AP	Kharif hybrid, 221 cm tall, White midrib colour, semi erect leaves, semi compact panicle, Tolerant to Charcoal rot, Ergot, Rust, shoot fly, aphids and stem borer. Non-lodging, & non-shattering, highly responsive for Deep soils.
	CSH 33		Nuziveedu seeds	Rajasthan, UP, North Gujarat, South Andhra Pradesh & TN	Kharif hybrid, 185 cm, early maturity, well exerted compact panicle, medium bold grain, Non-lodging, & non shattering tolerant to major pests and diseases.
	CSH 34		Hitech seeds	Maharashtra , Karnataka, MP, AP, Chattisgarh	Kharif hybrid, 210 cm tall, medium maturity, ear head – semi

				Gujarat, and Rajasthan	compact,, awn less, long bulging panicle, board in upper part to symmetrical in shape, white medium length stigma, creamy white medium bold grain, resistant to downy mildew, under natural conditions escapes grainmold due to little bit more maturity duration.
	CSH 35		Akola	Maharashtra , Karnataka, MP, South Gujarat, and Telangana	Kharif hybrid, 215 cmtall, medium maturity, ear head – semi compact, oblong withtapering apex; internodes covered by leaf sheath, dull green mid rib, non-lodging non shattering, moderately tolerant to major pests and diseases.
	CSV 24SS		ICAR-IIMR	All sorghum growingareas of India.	Sweet sorghum variety
	CSV 26 R		ICAR-IIMR (CRS)	Rabi season. Under shallow soil conditions of rabi sorghum growingareas of India.	Medium tall (183 cm) semi compact ear head, pearly white, lustrous seed, tolerant tocharcoal rot shoot fly, stem borer, shoot bug and sugarcane aphid And tolerant to terminal drought
	CSV 27		ICAR-IIMR	All sorghum growingareas of India.	Dual purpose kharif variety resistance to grain moulds non-lodging & non-shattering
	CSV 29R		Bijapur	Rabi sorghum growing areas of Maharashtra, Karnataka and Andhra Pradesh under Deep black soils	Tall (210 cm), semi compact cylindrical ear head, pearly white, lustrous seed, tolerant to charcoal rot, shoot fly, stem borer,shoot bug and sugarcane aphid.
	CSV 30F		Rahuri	All forage sorghum growing areas of India.	Forage Sorghum, Goose neck tendency of panicle observed sometimes due to environmental fluctuations
	CSV 31		Palem	Under rainfed conditions in Kharif season in Andhra Pradesh,Tamil Nadu, Rajasthan and Gujarat	Kharif variety, 210-250cm tall, juicy stem, white colourmid-rib, waxy bloom, semi-compact symmetric panicle, pearly white seed and grey yellow endosperm,tolerant to grain mold and resistant to anthracnose and leaf blight
	CSV 32F		ICAR-IIMR	All forage sorghum growing areas of Maharashtra, Tamilnadu and Karnataka (Zone II)	Forage Sorghum
	CSV 33MF		TNAU	All forage sorghum growing states (Zone-1&II)	Forage Sorghum, Tall, thinstem, high tillering, first cut after 62 days subsequent cut after 50 days, 1039 q/ha green fodder yield, 280 q/ha dry fodderyield resistant to leaf blight, anthracnose

USES

In India, the rainy-season sorghum grain is used mainly as animal/poultry feed, while the post-rainy-season sorghum grain is used primarily for human consumption (Reddy, 2017). Sorghum cultivation has been linked by archeological research to ancient Sudan around 6,000 to 7,000 BP. One species, *S. bicolor*, native to Africa with many cultivated forms, is a common crop worldwide, used for food (in the form of grain or sorghum syrup), animal fodder, the production of alcoholic beverages, and biofuels. In Nigeria, the pulverized red leaf-sheaths of sorghum have been used to dye leather, and in Algeria, sorghum has been used to dye wool (Wikipedia, 2023). Sorghum is cultivated in many parts of the world today. The grain finds use as human food, and for making liquor, animal feed, or bio-based ethanol. Sorghum grain is gluten free, high in resistant starch, and has more abundant and diverse phenolic compounds compared to other major cereal crops (Wikipedia, 2023).

Culinary uses: Sweet sorghum is the only crop providing grain and stem that can be used as substrates for the production of sugar, alcohol, syrup, fodder, fuel, bedding, roofing, fencing, and paper (Laopaiboon et al., 2007). The juicy stalks of sweet sorghum, which is similar to sugarcane is utilizing for preparation of syrup and jaggery. Sorghum grain is germinated, dried, and ground to form malt, which is used as a substratum for fermentation in beer production. A waxy sorghum identified in Mexico (a mutant variety that is nearly 100% amylopectin) may be advantageous for brewing; however, normal sorghum (approximately 75% amylopectin and 25% amylose) is more commonly used for beer production.

Sorghum grain is used for human food and as feed for animals; the plant stem and foliage are used for green chop, hay, silage, and pasture. In some areas the stem is used as building material, and plant remains (after the head is harvested) may be used for fuel (House, 1985). An unleavened bread prepared with flour ground from the grain is one of the most common foods made of sorghum. Sometimes the dough is fermented before the bread is prepared. Sorghum is also boiled into a porridoga orgruel. Beer is commonly made of the grain in many parts of Africa, often with grain of various colors. There are "specialty" sorghums, such as pop sorghum and sweet sorghum, that can be parched and eaten. These specialty sorghums are frequently grown as borders of large fields (House, 1985). Sorghum grain/flour is used to make Roti (unleavened bread), Sankati, Annam, Pops, and Ganji (thin porridge) in rural India. Some of the value-added sorghum products available commercially in India are sorghum-rich multigrain Atta, sorghum Rawa (fine and coarse rawa for Upma, Dosa and Idli), extruded products (Vermicelli and Pasta), flaking (breakfast cereal), baked products (Biscuits and Cookies) and instant mixes (Dosa mix, Idli mix and Pedamix) (Dayakar Rao *et al*.,2014). Sorghum grain is a staple food for millions of people in the semiarid regions of Africa and Asia where it is used to make food products such as tortillas, breads, cakes, noodles, couscous, beer and porridge. Sweet sorghum sap can be processed into sweeteners for the food industry or fermented into ethanol. Nearly all sorghum production (97%) in the western hemisphere is for livestock feed and forage because it is a lower cost alternative to maize and requires less water to grow. Developing countries also use sorghum plant products for cooking fuel, construction materials, leather dyes and as physical support for vining crops like yams (OECD, 2017).

Sorghum is cultivated for its grain, which is an important food source for people living in dry tropical and subtropical regions of the world. Sorghum grain, stems, and leaves are also used as livestock feed and fodder. Sorghum grain can be fermented to make beverages. Fermented sorghum beverages are traditionally brewed in parts of Africa (for example, *dolo*, *ikigage*, or *tchapalo*). Commercial brewers are also exploiting sorghum for use in gluten-free beers *(*Evolution, 2023*)*. Sweet sorghum or sorgo accumulates sucrose (a sugar) in its stem. Sweet sorghum stems can be crushed to extract the sugary juice, which can be processed into sorghum syrup. The juice can also be fermented and distilled to make sorghum rum. Sweet sorghum is of interest for producing biofuels, although it is not yet widely exploited for that purpose, unlike maize and sugarcane *(*Evolution, 2023*)*. Worldwide, sorghum is a food grain for humans. In the United States, sorghum is used primarily as a feed grain for livestock. Feed value of grain sorghum is similar to corn. The grain has more protein and fat than corn, but is lower in vitamin A. When compared with corn on a per pound basis, grain sorghum feeding value ranges from 90% to nearly equal to corn. The grain is highly palatable to livestock, and intake seldom limits livestock productivity. However, some sorghum varieties and hybrids which were developed to deter birds are less palatable due to tannins and phenolic compounds in the seed. The grain should be cracked or rolled before feeding to cattle; this improves the portion digested mm (Carter *et al.,* 2023). In many parts of Asia and Africa, sorghum grain is used to make flat breads that form the staple food of many cultures. Popped grains are a popular snack in parts of Western India. In India, where it is commonly called *jwaarie, jowar, jola*, or *jondhalaa*, sorghum is one of the staple sources of nutrition in Rajasthan, Punjab, Haryana, Uttar Pradesh, and the Deccan plateau states of Maharashtra, Karnataka, and Telangana. An Indian bread called *bhakri, jowar roti*, or *jolada rotti* is prepared from this grain. In Tunisia, where it is commonly called *drôô,* a traditional porridge dish is prepared with ground sorghum powder, milk, and sugar. The dish is a staple breakfast meal consumed in winter months. In Central America, tortillas are sometimes made using sorghum. Although corn is the preferred grain for making tortillas, sorghum is widely used and is well accepted in Honduras. White sorghum is preferred for making tortillas. Sweet sorghum syrup is known as molasses in some parts of the United States, although it is not true molasses. In Southern African countries, sorghum, along with milk, sugar and butter, is used to make Maltabella, a variation of millet porridge (Wikipedia, 2023).

Alcoholic beverage: In China, sorghum is known as *gaoliang* and is fermented and distilled to produce one form of clear spirits known as *baijiu* of which the most famous is Maotai (or Moutai). In Taiwan, on the island called Kinmen, plain sorghum is made into sorghum liquor. In several countries in Africa, including Zimbabwe, Burundi, Mali, Burkina Faso, Ghana, and Nigeria, sorghum of both the red and white varieties is used to make traditional opaque beer. Red sorghum imparts a pinkish-brown colour to the beer (Wikipedia, 2023).

Bio-based ethanol: In Australia, South America, and the United States, sorghum grain is used primarily for livestock feed and in a growing number of ethanol plants. In some countries, sweet sorghum stalks are used for producing biofuel by squeezing the juice and then fermenting it into ethanol. Texas A&M University in the United States is currently running trials to find the best varieties for ethanol production from sorghum leaves and stalks in the USA (Wikipedia, 2023).

Agricultural uses: It is used in feed and pasturage for livestock. Its use is limited, however, because the starch and protein in sorghum is more difficult for animals to digest than the starches and protein in corn. One study on cattle showed that steam-flaked sorghum was preferable to dry-rolled sorghum because it improved daily weight gain. In hogs, sorghum has been shown to be a more efficient feed choice than corn when both grains were processed in the same way (Wikipedia, 2023).

Animal feed: Sorghum is an excellent feed for livestock and companion animals. The feeding value of sorghum for livestock species is generally considered 95% or more of the feeding value of yellow dent maize. Brown sorghums are considered to have 80–85% the feeding value of maize. Sorghum must be properly processed to enhance its digestibility. Popping, steam flaking, and reconstitution are used to prepare sorghum grain in beef cattle feedlots in the USA. Grinding, rolling, crushing, and pelleting are used for poultry and swine feeds. Sorghum has a proximate composition, amino acid contents, and nutritional value similar to those of maize. However, due to its lower fat content, sorghum usually has a slightly lower gross, digestible, and metabolizable energy. Lysine and threonine are the first and second limiting amino acids. Most sorghum hybrids do not contain condensed tannins in contrast to impressions given in some publications. Kernels that contain condensed tannins have a clearly pigmented, thick testa. These sorghums are classed as brown or tannin sorghums. The brown sorghums are grown in some areas where birds and molds are major problems. Birds will consume brown sorghums when other foods are scarce. Animals fed brown sorghum rations eat more feed and produce about the same amount of gain so feed efficiency is reduced significantly. Sorghum used as a feed grain is generally softer than that used for food grain; its grain is often colored. It is seldom fed without coarse grinding or breaking-other processes involve various soaking procedures, flaking, and popping. The purpose is to expose a larger portion of the seed to the animal's digestive enzymes. If not treated, some grain (when used as feed) will pass through the animal undigested (House, 1985). The sorghum plant makes good feed. It can be chopped for silage or fed directly to the animals. Sudangrass is used as pasture and made into hay. The stover-the portion remaining after the head Is removed-is often used as hay. This, however, Is poorer In quality than stover from sorghum managed as a feed crop (House, 1985). Cyanide can be produced in poisonous quantities by some sorghum and Sudan grass. The cyanide concentration is greatest in seedling plants and declines as the plant grows: it is low after 30 to 40 days of growth and virtually absent just before heading. The concentration of cyanide is most serious in new growth following cutting. The greatest danger occurs if regrowth is damaged by frost. The cyanide problem can be managed by careful attention to selection of varieties low in cyanide, and by proper grazing. Presence of cyanide need not be a serious restriction to the use of sorghum forage for feed (House, 1985).

The stover (mature cured stalks of corn with the ears removed that are used as feed for livestock) remaining after harvesting the grain is cut and fed to cattle, sheep and goats, or may be grazed. Some farmers grind harvested stover and mix it with sorghum bran or salt to feed livestock. Brown midrib (BMR) lines of *Sorghum bicolor* were used as forage sources for livestock because of their reduced lignin content and higher digestibility of the stover. Broom sorghum (broomcorn, *S. vulgare*) is also used as a source of animal feed in some regions, although it is less digestible than *S. bicolour*. Sudan grass and its hybrids may be used as pasture, hay, green chop, or silage for livestock. Sweet sorghums are used for the production of syrup or molasses, and are being considered as potential sources for fuel ethanol. Production of ethanol from sorghum grain or sweet sorghum biomass (stalks) has gained increasing interest in recent years. To produce ethanol from sorghum grain, the whole grain is ground, gelatinized, and converted to fermentable carbohydrates using enzymes. The product, distillers' grains, contains approximately 30% protein, and is commonly used as feed for livestock in either wet or dry form (Balakrishna and Bhat, 2016).

Pasturing cattle or sheep on sorghum stubble, after the grain has been harvested, is a common practice. Both roughage and dropped heads are utilized. Stubble with secondary growth must be pastured carefully because of the danger of prussic acid (HCN) poisoning (Carter et al., 2023). Grain sorghum may also be used as whole-plant silage, however another sorghum, sweet sorghum, was developed as a silage crop. Sweet sorghum produces much higher forage yields than grain sorghum, but feed quality will likely be lesser because there is no grain. Some growers mix grain sorghum with soybeans to produce a higher protein silage crop (Carter *et al.*, 2023). In the early stages of plant growth, some sorghum species may contain levels of hydrogen cyanide, hordenine, and nitrates lethal to grazing animals. Plants stressed by drought or heat can also contain toxic levels of cyanide and nitrates at later stages in growth (Wikipedia, 2023).

Industrial uses: Sorghum grain or sweet sorghum biomass is used for ethanol production. Yields of alcohol (182° proof) per tonne of sorghum grain are comparable with maize (387 vs. 372 L). The commercial technology required to ferment sweet sorghum biomass into alcohol has been developed in Brazil to extend the mill season and complement sugarcane production. One tonne of sweet sorghum biomass has the potential to yield 74 L of 200° proof alcohol. In Southern and West Africa, sorghum malt is used for alcoholic and non-alcoholic beverages, weaning foods, and breakfast foods. Sour-opaque beers are produced commercially in Southern Africa. Opaque beer is produced following the basic steps of the traditional process. Breweries in Mexico, Africa, and Asia use sorghum grits as an adjunct in brewing lager beer. In Nigeria, sorghum and maize are used to produce lager or clear beer without barley malt. Nigerian breweries produce clear beer from a combination of malted sorghum, sorghum, and/or maize grits with commercial enzymes to convert the starch to fermentable sugars because sorghum malt has a low diastatic power. The same approach is now used by several U.S.-based brewers to produce a sorghum-based gluten-free lager beer for targeted to individuals with allergic reactions to gluten. The quality of clear beer is good, but the taste differs from barley malt beer. Sorghum grits, meal, and flour can be used alone or mixed with wheat flour to produce an array of baked goods. However, sorghum does not contain gluten so the amount of sorghum flour in the blends depend on the quality of the wheat flour, baking procedure, formulation, and quality of the baked products desired. New food-type sorghums that produce excellent yields of flour with a bland flavor and light color are available. They can be used to extend wheat-based products without affecting flavor. Sorghum can be puffed, popped, shredded, and flaked to produce ready-to-eat breakfast cereals. Extrusion of sorghum produces acceptable snacks and precooked products. In the Sudan, sorghum is wet-milled to produce starch with properties and uses similar to those of maize starch. Commercial wet milling of sorghum in the USA was discontinued in the 1970s because of poor economics. Specific types of sorghum are used to produce a sweet sorghum syrup comprised of sucrose, glucose and fructose. This sugar is extracted from the stalk and cooked to concentrate the soluble sugars in the juice. The enzymatic conversion of starch from sorghum grain to liquid glucose syrup is also possible.

Other uses: It is also used for making a traditional corn broom. The reclaimed stalks of the sorghum plant are used to make a decorative millwork material marketed as Kirei board (Wikipedia, 2023). Broomcorn inflorescences are used in some types of decorations, as well as in natural-bristle brooms (Evolution, 2023). Some of the products prepared from Sorghum is given in Fig.17

Sprouts

Roti

Bhakri (flat bread) made from jowar (sorghum) flour

Upama

Porridge

Tchoukoutou, a fermented beverage

Grits (ground maize) and milk with sorghum syrup

Popped sorghum

Boiled

RTS Sorghum based beverage

Tamarind-Sorghum sauce

Sorghum based mixed jam

Sorghum based toffee

Sorghum based tamato sauce

Multi gairn cookies with sorghum

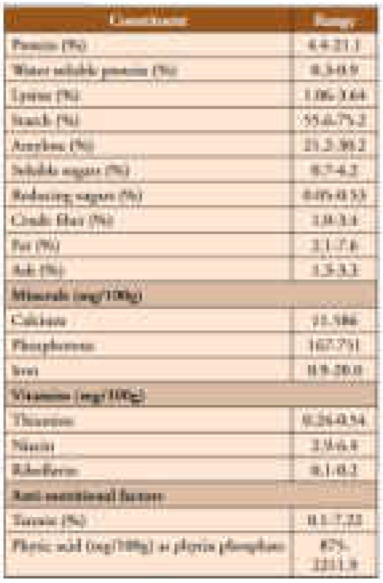
Fig. 17. Products prepared from Sorghum

NUTRITIONAL VALUE

Sorghum is one of the cheapest sources of energy and micronutrients, and a vast majority of the population in sub-Saharan Africa and India depend on it for their dietary energy and micronutrient requirement. Sorghum provides more than 50 % of the dietary micronutrients, particularly Fe and Zn, to the low-income group, particularly in rural India where both physical and economic access to nutrient-rich foods is limited. Thus, sorghum is a unique crop with multiple uses as food, feed, fodder, fuel, and fiber (Kumar, 2016).

Constituents of Sorghum are given in **Table 9** (Balakrishna and Bhat, 2016).

Table 9. Constituents of Sorghum



Constituent	Range
Protein (%)	4.4-21.1
Water soluble protein (%)	0.3-0.9
Lysine (%)	1.06-3.64
Starch (%)	55.6-75.2
Amylose (%)	21.2-30.2
Soluble sugars (%)	0.7-4.2
Reducing sugars (%)	0.05-0.53
Crude fiber (%)	1.0-3.4
Fat (%)	2.1-7.6
Ash (%)	1.3-3.3
Minerals (mg/100g)	
Calcium	11-586
Phosphorus	167-751
Iron	0.9-20.0
Vitamins (mg/100g)	
Thiamine	0.24-0.54
Niacin	2.9-6.4
Riboflavin	0.1-0.2
Anti-nutritional factors	
Tannin (%)	0.1-7.22
Phytic acid (mg/100g) as phytin phosphorus	875-2211.9

Nutritional value per 100 g Sorghum grain is given in **Table 10** (Wikipedia, 2023).

Energy	329 kJ (79 kcal)
Carbohydrates	72.1 g
Sugars	2.53 g
Dietary fiber	6.7 g
Fat	3.46 g
Saturated	0.61 g
Monounsaturated	1.13 g
Polyunsaturated	1.56 g
Protein	10.6 g
Vitamins	**Quantity %DV** †
Vitamin A equiv.	0% 0 μg
Thiamine(B1)	29% 0.332 mg
Riboflavin (B2)	8% 0.096 mg
Niacin (B3)	25% 3.69 mg
Pantothenic acid (B5)	7% 0.367 mg
Vitamin B6	34% 0.443 mg
Folate (B9)	5% 20 μg
Vitamin C	0% 0 mg
Vitamin E	3% 0.5 mg
Minerals	**Quantity %DV** †
Calcium	1% 13 mg
Copper	14% 0.284 mg
Iron	26% 3.36 mg
Magnesium	46% 165 mg
Manganese	76% 1.6 mg
Phosphorus	41% 289 mg
Potassium	8% 363 mg
Selenium	17% 12.2 μg
Sodium	0% 2 mg
Zinc	18% 1.67 mg
Other constituents	**Quantity**
Water	12.4 g

Table 11. Nutritional composition of Sorghum grains per 100 g

Nutritional composition of sorghum grain per 100g	
Nutrient	Content
Energy (Kcal)	342
Carbohydrates (g)	72.7
Proteins (g)	10
Fats (g)	3.7
Fiber (g)	2.2
Calcium (mg)	22
Iron (mg)	3.8
Phosphorus (mg)	242
Sodium (mg)	8
Potassium (mg)	44
Zinc (mg)	1.5
Vitamin C (mg)	0
Vitamin B1 or thiamin (mg)	0.33
Vitamin B2 or riboflavin (mg)	0.18
Vitamin B3 or niacin (mg)	3.9

The grain is edible and nutritious. It can be eaten raw when young and milky, but has to be boiled or ground into flour when mature. Sorghum grain is 72% carbohydrates including 7% dietary fiber, 11% protein, 3% fat, and 12% water (table). In a reference amount of 100 grams (3.5 oz), sorghum grain supplies 79 calories and rich contents (20% or more of the Daily Value, DV) of several B vitamins and dietary minerals. All sorghums contain mixed polyphenols, such as phenolic acids and flavonoids. Sorghum grains are one of the highest food sources of proanthocyanidins (Wikipedia, 2023). *S. bicolor* is rich in minerals like phosphorus, potassium and zinc. The nutritional values of *S. bicolor* are comparable to those of rice, corn and wheat. The energy value of 100 g *S. bicolor* grains ranges from 296.1 to 356.0 kcal. The grains contain 60 – 75% carbohydrates, 8 – 13% protein and 4 – 6 % fat. The saccharose and glucose content in the stalk is 10 – 16%. In comparison sugarcane has a sugar content of 10 - 20%. Thus *S. Bicolor* can be used as an alternative to sugar cane. The low starch digestibility of sorghum is caused by the association between the starch granules with the proteins and tannins. The digestibility of the proteins is lower than those of wheat and corn. In contrast to the prolamins of wheat, rye and barley, the kafirins of sorghum do not provoke allergic reactions or autoimmune response in humans. Furthermore, the properties of sorghum inhibit the expression of toxic peptides related to gliadin, making *S. bicolor* a safe grain for consumption by people with celiac disease. Jowar is the finest substitute for wheat and rice when it comes to nutrition because it has high levels of thiamine, niacin, riboflavin, and folate (Wikipedia, 2023).

HEALTH BENEFITS

Sorghum is a coarse grain, primarily used as food in semi-arid tropics and sub tropics of Asia and Africa and an important feed grain and fodder crop in the Americas and Australia. Sorghum is the principle source of energy, protein, vitamin, minerals, and trace elements for millions of the poorest people. Sorghum grain has certain properties that make it suitable to be consumed by people suffering from chronic disorders. The nutritional value along with specific nutrients in the grain has been found to prevent and control life style diseases and disorders. Gluten-free sorghum food is recommended for gluten-intolerance and celiac patients, relatively low glycemic index and low glycemic sorghum food reduces the risk of diabetes. Sorghum has low fat content and rich source of antioxidants, polyphenols, dietary fiber, and magnesium (Ciacci *et al.,* 2007; Dayakar Rao *et al.,* 2014)

The following health benefits have been reported by Dayakar *et al.* (2014):

Celiac disease (CD) is an immune-mediated enteropathy triggered by the ingestion of gluten in genetically susceptible individuals and is one of the most common lifelong disorders worldwide. Consumption of gluten free sorghum products can be suitable for individuals suffering from celiac disease. Sorghum is rich in dietary fiber and has low glycemic index, which help in the lower plasma glucose level and control of diabetes. Consumption of sorghum may have positive health impact on people suffering from cancer.

Natural toxicants in Sorghum: Sorghum can contain a cyanogenic glycoside that can produce Hydrogen cyanide (HCN) during times of stress or if damaged by frost or mastication. Sorghum can also accumulate toxic levels of nitrates. Cattle and rarely horses have been poisoned.

Allergens in Sorghum: Sorghum pollen sensitivity has been recognized as a potential health problem in causing bronchial asthma.

Allelopathic properties in Sorghum: Sorghum is well recognized for its allelopathic effects on other crops and mature sorghum plants possess a number of water soluble allelochemicals

The following health benefits have been reported by WMDEC (2022):

Anti-inflammatory effects: Sorghum is known to be rich in phenolic compounds, many of which act as antioxidants. It has also been shown to be good at reducing some forms of inflammation due to its antioxidant properties.

Anti-cancer effects: Several of the phenolic compounds in sorghum have been linked to anti-cancer effects. The tannins in sorghum, which contribute to the grain's pigmentation, may inhibit an enzyme linked to the development of breast cancer. Another set of phenolic compounds found in sorghum, known as 3-deoxyanthocyanidins, have been shown to have a destructive effect on some human cancer cells.

Weight loss: The starches in sorghum are difficult for the human body to digest, compared to other grains. As a result, sorghum is an excellent addition to any meal, helping you feel full without contributing too many calories to your diet.

Safe for celiac disease: Sorghum and its byproducts, including sorghum flour, have been determined to be a safe alternative grain for those with Celiac's disease. The biggest health risk of sorghum is tied to its potential as an allergen.

Sorghum allergy: Allergies associated with grasses and grass pollen are extremely common. Unfortunately, Sorghum is a grass and is known to produce an allergic reaction in some people. Food allergy symptoms include tingling or itching of the mouth, swelling in and around the mouth, abdominal pain, nausea, vomiting, and even fainting. Severe allergic reaction or anaphylaxis can result in any food allergy and can be life-threatening.

The following health benefits have been reported by HBS (2023):

Sorghum may inhibit cancer tumor growth: Compounds in sorghum called 3-Deoxyanthoxyanins (3-DXA) are present in darker-colored sorgums, and to a lesser extent in white sorghum. Scientists at the University of Missouri tested extracts of black, red, and white sorghums and found that all three extracts had strong antiproliferative activity against human colon cancer cells.

Sorghum may protect against diabetes and insulin resistance: Advanced glycation endproducts (AGEs) are increasingly implicated in the complications of diabetes. A study from the University of Georgia Neutraceutical Research Libraries showed that sorghum brans with a high phenolic content and high anti-oxidant properties inhibit protein glycation, whereas wheat, rice or oat bran, and low-phenolic sorghum bran did not. These results suggest that "certain varieties of sorghum bran may affect critical biological processes that are important in diabetes and insulin resistance."

Sorghum is safe for people with celiac disease: Up to one percent of the U.S. population (and about ½% worldwide) is believed to have Celiac Disease, an autoimmune reaction to gluten proteins found in wheat, barley and rye. While sorghum has long been thought safe for celiacs, no clinical testing had been done until researchers in Italy made a study. First, they conducted laboratory tests; after those tests established the likely safety, they fed celiac patients sorghum-derived food products for five days. The patients experienced no symptoms and the level of disease markers (anti-transglutaminase antibodies) was unchanged at the end of the five-day period.

Sorghum may help manage cholesterol: Scientists at the University of Nebraska observed that sorghum is a rich source of phytochemicals, and decided to study sorghum's potential for managing cholesterol. They fed different levels of sorghum lipids to hamsters for four weeks, and found that the healthy fats in sorghum significantly reduced "bad" (non-HDL) cholesterol. Reductions ranged from 18% in hamsters fed a diet including 0.5% sorghum lipids, to 69% in hamsters fed a diet including 5% sorghum lipids. "Good" (HDL) cholesterol was not affected. Researchers concluded that "grain sorghum contains beneficial components that could be used as food ingredients or dietary supplements to manage cholesterol levels in humans."

Advantages of sorghum over maize in south african diets: Sorghum has been widely consumed as a staple food and in beverages throughout Africa. More recently, corn has replaced sorghum in some areas. Researchers from the University of Witwatersrand Medical School in South Africa believe that "the change of the staple diet of Black South Africans from sorghum to maize (corn) is the cause of the epidemic of squamous carcinoma of the esophagus." They link the cancers to Fusarium fungi that grow freely on maize but are far less common on sorghum and note that "countries in Africa, in which the staple food is sorghum, have a low incidence of squamous carcinoma of the esophagus."

Antioxidants in sorghum high relative to other grains and to fruits: Joseph Awika and Lloyd Rooney, at Texas A&M University, conducted an extensive review of scores of studies involving sorghum, and concluded that the phytochemicals in sorghum "have potential to signiciantly impact human health." In particular, they cited evidence that sorghum may reduce the risk of certain cancers and promote cardiovascular **health.**

Sorghum may help treat human melanoma: Scientists in Madrid studied the effect of three different components from wine and one from sorghum, to gauge their effects on the growth of human melanoma cells. While results were mixed, they concluded that all four components (phenolic fractions) "have potential as therapeutic agents in the treatments of human melanoma" although the way in which each slowed cancer growth may differ.

The following health benefits have been reported by Americansorghum (2023): High nutritional value: Sorghum has a whopping 22 grams of protein in a 1 cup (192 gram) serving of the cooked, whole grain. A woman's daily recommended protein intake is 46 grams and a man's is 56 grams. On average, that means sorghum contains 43 percent of your daily protein intake. One serving also contains 47 percent of your daily recommended iron and 55 percent of your phosphorus intake. It's also a good source of magnesium, copper, calcium, zinc and potassium. A serving of sorghum also contains around 30 percent of your recommended intake of both niacin and thiamin. These two B-vitamins help us to metabolize and properly absorb carbohydrates and nutrients.

Rich in antioxidants: Sorghum contains a wide variety of beneficial phytochemicals that act as antioxidants in the body, such as tannins, phenolic acids, anthocyanins, phytosterols and policosanols. In fact, the bran layer of sorghum has significantly higher amounts of antioxidants than fruits such as blueberries, strawberries and plums. Antioxidants help to slow down aging and antioxidant-rich foods have been linked to a lower risk of heart disease, cancer, type II diabetes, and some neurological diseases as well. Many studies indicate that whole grain consumption significantly lowers mortality from cardiovascular disease. Antioxidant phytochemicals are believed to be the main reason and they have been shown to reduce blood cholesterol and prevent arterial clotting.

Improves digestive health: Sorghum is one of the best sources available for dietary fiber. One serving contains 48 percent of your daily recommended intake of fiber. Fiber is vital for overall digestive function. It keeps your digestive tract moving and of course prevents constipation. But it also helps to regulate blood sugar, lower cholesterol, and prevent diverticulitis, hemorrhoids, gallstones and kidney stones.

Inhibits cancer: Certain phytochemicals in sorghum have also been shown to have cancer-inhibiting properties, particularly in gastrointestinal and skin cancers. Studies have shown that sorghum consumption is linked to lower incidences of esophageal cancer globally, including parts of Africa, Russia, India, China and Iran. Wheat and corn consumption have been linked to elevated rates of esophageal cancer. Whole grains in general are correlated with reduced risks of other forms of digestive tract cancer, especially colon cancer. It is unknown if this is due to the phytochemicals or dietary fiber in grains, but as sorghum is high in both, it would certainly provide the same benefits as other grains.

Gluten-free: Sorghum is safe to eat for those with Celiac disease. The Journal of Agricultural and Food Chemistry published a study that analyzed the genome of sorghum to determine if it contained any gluten proteins. They confirmed that gluten is absent in all varieties of sorghum.

Currently non-genetically modified: Another benefit of sorghum is that it's a non-genetically modified crop.

Although, the company DuPont Pioneer is working to develop a genetically modified (GM) variety. Most plant genetic engineering to date has been to improve a crop's herbicide tolerance and resistance to pests. DuPont is working on a new type of genetic engineering to enhance the micronutrient content of sorghum. Their goal is to develop a "biofortified" strain of sorghum with higher vitamin A, more easily absorbed iron and zinc, and an improved balance of amino acids. They have already grown trial GM sorghum crops in Africa. GM sorghum is not grown in North America yet, but always buy certified organic sorghum products when you can find them. This will ensure there is no GM material present, as well as avoiding harmful pesticide residues.

Many uses: Sorghum is a very versatile grain. It is best eaten in its whole grain form to get the most nutrition. It can be prepared similar to rice. Try soaking whole sorghum for 8 hours or overnight to first break down the enzymes and make it more digestible. Then boil it in three times as much water for about an hour or until tender. It can also be cooked in a rice steamer or slow cooker. Sorghum flour is becoming a popular gluten-free substitute for wheat flour in baked goods. Make sure you buy the whole grain form of sorghum flour, which is simply the whole grains ground into flour. Refined sorghum flour is also available, but like most refined products, the nutrient content is reduced. In some countries, sorghum is eaten as porridge or boiled directly into various dishes. The Ethiopian bread injera can be made from sorghum, as well as many gluten-free beers and even biofuels. As its popularity rises, sorghum is becoming much more common in grocery stores and markets. It's definitely a grain that deserves a place at our tables.

The following health benefits have been reported by PPP (2023):

Sorghum aids in digestion: Adding a serving or two of sorghum to your daily diet can do your digestive system a world of good! A serving of sorghum contains 48% of the recommended daily intake of fiber! Fiber is the ultimate body regulator, helping food stay its course through your digestive system. Adequate fiber intake also prevents constipation, diarrhea, bloating, cramping and other digestive issues. Fiber also helps to eliminate bad cholesterol from the body, which contributes to heart health.

Sorghum boosts energy: While all grains technically give you energy, sorghum wins the blue ribbon in our hearts. Sorghum is an excellent energy source because it is considered a complex carbohydrate, which provides sustained energy for several hours. Sorghum also contains niacin, or vitamin B3, which is known to help convert food to energy.

Sorghum promotes bone health: We've got good news for your vegetarians out there: sorghum makes it easier for people who rely on a plant-based diet to consume and absorb key nutrients that contribute to bone health. Sorghum contains both magnesium and calcium, which help to promote bone health. Magnesium increases the absorption of calcium in your body, while calcium actually builds your bones.

Sorghum prevents cancer: Sorghum transforms your pantry into your medicine cabinet, since it contains disease-fighting nutrients like antioxidants. Sorghum is full of phytochemicals, which are antioxidants that prevent certain types of cancer (skin cancer, colon cancer, and esophageal cancer, to name a few). Phytochemicals are also excellent for maintaining cardiovascular health.

Sorghum is safe for gluten intolerance: The USDA recognizes sorghum as 100% gluten-free, meaning it's safe for people with Celiac's Disease and gluten intolerance to eat on a regular basis. Both sorghum flour and whole-grain sorghum are great substitutes for wheat-based recipes. With their, light, nutty flavor, sorghum also has no problem taking the spotlight in traditional dishes.

Sorghum increases circulation: Sorghum contains iron, copper, zinc, and magnesium, which all have a hand in improving circulation. Copper helps the body absorb iron better, which can prevent anemia. Having plenty of iron and copper in your body helps with circulation and stimulates cell growth and repair. Iron and copper also help maintain energy levels.

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