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Research Article

SWEET SORGHUM FOR BIOFUEL ENERGY: GRAIN SORGHUM FOR FOOD AND FODDER-PHYTOCHEMISTRY AND HEALTH BENEFITS

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ABSTRACT

This review of literature highlights about commercial utilization of the bicolor race of sorghum. **Sorghum bicolar** is a complex, heterogeneous and consists of several distinct subraces. These include sweet sorghum, a C4 herbaceous annual grass and multipurpose crop, which consist of sweet-stalked cultivars suitably harnessed for producing value-added products like jaggery, syrup and bioethanol, besides being used for food, feed and fiber. **Nimbkar Agricultural Research Institute** (NARI) pioneered the development of sweet sorghum after introducing it to India in the mid-1970s. **NARI** was the first in India to produce ethanol from sweet sorghum juice developing the complete technology from crop growing to solar-powered ethanol distillation. **Ethanol** produced from **sweet sorghum is safer** for environment **due to low sulphur content, low biological and chemical oxygen demand** and **high octane rating.** The **International Crops Research Institute for the Semi-Arid Tropics** (ICRISAT), India has made the first major attempt in India to evaluate and identify the useful high biomass producing sweet sorghum germplasm from world collections. ICRISAT has contributed many hybrid high sugar sweet sorghum varieties. Most **hybrids** of sweet sorghum are relatively **less photoperiod- sensitive. Cytoplasmic male sterility** has been found in sorghum (A1–A4 systems) which has made possible the development of a hybrid seed industry. Grain sorghum is a **gluten-free cereal**, primarily served as food for humans or livestock feed. Sorghum is the only dietary source for **3-Deoxyanthocyanidins** (3-DXAs). Sorghum grains have antioxidative, anticancer, antidiabetic, anti-inflammatory, and antiobesity health benefit properties. **High fiber** content and **poor digestibility** of nutrients is a characteristic feature of sorghum grains.

Keywords: Antinutrients, bioethanol, grain sorghum, Karnataka, ICRISAT, NARI, India, sweet sorghum,.

INTRODUCTION

Sweet sorghum [*Sorghum bicolor* (L.) Moench] is a well known universal multipurpose crop for food, fodder and potential bio-fuel feedstock (1-36, 47-59). Sorghum (*Sorghum bicolor* (L) Moench) is the fifth important cereal crop in the world in production and fifth in acreage after wheat, rice, maize and barley (1-39, 47-59). India is the third largest producer after USA, and Nigeria (1-59). Sorghum is well adapted to the semi-arid tropics and is one of the most efficient dry land crops to convert atmospheric CO_2 into sugar (1-36, 47-59). In terms of area, India (7.5 m ha) is the largest sorghum grower in the world followed by USA, Nigeria (7.6 m ha) and Sudan (6.6 m ha) (1-39, 47). Sweet sorghum accumulates high concentrations of soluble sugars (10–15 %) in the plant stalk sap or juice (1-36, 47-59). However, proportion and composition of sugar content in sweet sorghum stalks is a critical factor when considering it as a potential biofuel feedstock (1-59). Increased sugar content is reported to be dominant or additive trait (1-47-59). Sweet sorghum (*Sorghum bicolor* L. Moench) is a **C_4** herbaceous annual grass that is cultivated from the seed is known by different names such as climate change ready crop, **miracle crop**, a smart crop **or sugarcane of the desert"** or "the camel among crops (1-39, 47-52-59).

Sweet sorghum is widely cultivated in USA, India, Brazil, China, Mexico, Sudan, Argentina, and many other countries in Asia and Europe. Like grain sorghum, it has its origin in Africa (1-52). The highest genetic and phenotypic diversity in both wild and cultivated accessions of sorghum are found in the central Africa (1-59). Many natural variants and hybrid cultivars suited to diverse agro-climatic conditions worldwide have been developed using conventional breeding technologies (1-58). Sweet sorghum is an annual plant with a short life cycle of about 4 months. It allows two crops per year though optimal planting date varies with the place of cultivation and the variety (1-47). It is a warm-season crop with the highest productivity in rainy and summer seasons. Sweet sorghum is mainly adapted to arid and semi-arid regions (1-59).

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Sweet Sorghum: Commercially Important Crop

Sweet sorghum is a plant based solution to the **bio-fuel** issue. Sweet sorghum, similar to grain sorghum except for its juice-rich sweet stalk, is being grown in USA (for syrup) and Africa (for fodder), and bio-ethanol feedstock, expected to meet food, fodder, fuel and fibre demands (1-50, 104-148). Grain sorghum is traditionally under cultivation for nearly 3,000 years (1-39, 47-52). Sweet sorghum can be grown easily on all continents, grows well in diverse agro-ecologies, in tropical, sub-tropical, temperate, semi-arid regions as well as in poor quality soils, low fertilizer and water requirement due to drought hardy characteristics, where other crops failed to thrive and are highly suitable for cultivation in tougher dry land growing areas (1-48). It can be grown as a rain-fed crop (1-47). Sweet sorghum can produce very high yields with irrigation. Yield of sweet sorghum is directly affected by the planting time (1-47, 104-148). It is a warm-season crop with the highest productivity in rainy and summer seasons (1-36, 47-52). Although moisture availability is critical for the plant growth (1-47). Sweet sorghum is relatively drought-tolerant and can be adapted to grow on marginal lands with low water availability (1-36, 47-59, 104-148).

Its **ratooning** ability enables multiple harvests per season, a feature that could expand the geographical range of sorghum cultivation (1-39, 47-52). Sweet sorghum experiences a short vegetative period at a very high photosynthetic rate (1-52). Therefore, sweet sorghum can produce more sugar than any other crop (1-47, 104-152). It experiences a little disease or pest attacks, and produces good cash flow at a low investment per acre (1-52). Sorghum is a 4 month duration plant and can be cultivated 2–3 times a year. Sweet sorghum is tolerant to biotic and abiotic stresses such as drought, temperature and salinity (1-47, 104-148).

How Sweet sorghum is different

Sweet sorghum syrup is being marketed under ''**Madhura**'' brand name (1-36, 47). No sweet sorghum variety is recommended for commercial production under rabi conditions in India. ***Madhura-2* is the first high-yielding genotype found to be suitable for growing under rabi conditions.** Since it gives high sugar in the stalk in addition to grain, its popularization under rabi conditions would greatly enhance monetary returns from the crop to the farmers. The higher income from sweet sorghum than grain sorghum would encourage its production under rabi conditions in traditional and non-traditional areas of sorghum in the country (1-50, 104-148). Sweet sorghum bagasse was also tested in an existing paper mill to assess its suitability for paper manufacture (1-47). Sweet sorghum has some interesting characteristics: Its growth cycle is short (about four months) facilitating double cropping (1-47, 104-148). It can be easily grown from seeds. Its production can be completely mechanized (42). It produces sugar in the stalk and starch in the grain (1-52). It has a high water and nutrient use efficiency (1-52, 104-148). The bagasse produced from sweet sorghum has a high biological value when used as a forage (1-49, 104-148). It has a wide adaptability to different environments (42). Commercial cultivars of *Sorghum bicolor* (L.) Moench are categorized into the different agronomic variants (42); Grain sorghum, Forage (or fodder) sorghum, Fibre sorghum, Broom sorghum, Sweet sorghum, Biomass sorghum (1-42-52, 104-148).

The term **sweet sorghum** is used to distinguish varieties of sorghum with high concentrations of soluble sugars in the plant stalk sap or juice compared to grain sorghum which has relatively less sugar and juice in the stalks (1-52, 104-148). The sweet sorghum value chain basically involves four critical areas i.e. feed stock supply, sugars conversion, bio-energy (ethanol blended gasoline) distribution and use (1-39, 47-52, 104-148). In a feedstock like sweet sorghum, whole plant, its products and by-products are used for diverse purposes (1-52, 104-148). Sweet sorghum is mainly cultivated for syrup production or forage, whereas other sorghum varieties such as kafirs and milos are cultivated for grain production (1-52). It has wide flat leaves and a round or elliptical panicle with full of grain at maturity (1-39, 47-52).

Sorghum is a dry land crop, sufficient moisture availability for plant growth is critically important for high yields (1-39, 47-58, 104-148). The major advantage of sorghum is that it can become **dormant** especially in **vegetative phase** under adverse conditions and can resume growth after relatively severe drought (1-39, 47-52). Early drought stops growth before panicle initiation and the plant remains vegetative (1-40, 47, 104-148). Sorghum will resume leaf production and flower when conditions again become favorable for growth. Mid-season drought stops leaf development. Sorghum is susceptible to sustained flooding, but will survive temporary water logging much better than maize (1-40, 47-52, 104-148). Most **hybrids of sweet sorghum** are relatively **less photoperiod- sensitive** (1-39, 47). Traditional farmers, particularly in West Africa, **used** photoperiod sensitive varieties (1-46, 47-52). With **photoperiod-sensitive types**, flowering and grain maturity occurs almost during the same calendar days regardless of planting date, so that even with delayed sowing, sorghum plants mature before soil moisture is depleted at the end of the season (1-58, 104-148). Sweet sorghum can be grown under dry land conditions with annual rainfall ranging from 550−750 mm (1-26). The best areas to produce this crop are central and south India, subtropical areas of Uttar Pradesh and Uttaranchal (17-26, 104-148). It can be grown on well drained soils such as silt loam or sandy silt clay loam soils with a depth ≥0.75m. Atmospheric temperatures suitable for sweet sorghum growth vary between 15 and 37°C (1-26). Sorghum in general has relatively deep root system (>1.5 m), and has the unique feature of becoming "**Dormant" under unfavourable** conditions and resuming growth once environmental conditions are favourable for growth (1-59).

Sweet Sorghum: Historical Origin

Sorghum, a wild grass plant of **African origin** is a drought-resistant and heat-tolerant member of the grass family, Poaceae (1-15). Wide varieties in the genus sorghum were observed in the North Eastern regions of Africa comprising of Ethiopia and Sudan in Eastern Africa (1-49). Historically the **Bantu tribe** carried this sorghum crop with them to the Savannah regions of Western and Southern Africa who used the sorghum grain mainly for making **beer** and extended to Tanzania, Cameroon region, and Congo belt (1-40). During the **first millennium BC**, sorghum was probably **carried to India** from Eastern Africa in ships as food (1-47). The sorghum varieties of India bear relationship to those existing in North-Eastern Africa and the coast between Cape Guardafui and Mozambique (1-47). Further sorghum spread along the coast of Southeast Asia and reached China around the beginning of Christian era (1-38). Later sorghum made its way to Western parts of the World and Australia via Asia (1-47). Sweet sorghum was introduced in 1853 by William Prince, a **New York Nurseryman** who received some seed from France via China and cultivated the sorghum crop in New York (1-40). The sweet sorghum varieties introduced **by William Prince and J.D. Browne** were termed as ''Black amber'' or ''Chinese sugarcane'' since they arrived in America though France via China (1-39). Subsequently, sorghum production was established in the **United States** to a larger extent with the introduction of grain sorghum variety in California in **1874** (1-47).

Sorghum: Taxanomy

The name Sorghum bicolor (L.) Moench was proposed by **Clayton in 1961** as the correct name for the cultivated sorghum which is currently in use (1-38, 47-52). The genus sorghum is a variable complex genus belonging to the tribe Andropogoneae of subgroup Panicoideae of the grass family, Poaceae which comprises of **24 species** with various chromosome numbers and are subdivided into **five sub-generic** sections based upon node, panicle and spikelet morphology (1-43, 47). The genus *Sorghum* is divided into **five subgenera** including *Sorghum*, *Stiposorghum Chaetosorghum*, *Heterosorghum*, and *Parasorghum* (1-53). The subgenus *Sorghum* contains three species including *S. bicolor*, *S. propinquum*, and *S. halepense* (1-47, 52). Further, *S. bicolor* has three subspecies including *S. bicolor*, *S. bicolor drummondii*, and *S. bicolor verticilliflorum* (formerly referred as *arundinaceum*). *Sorghum bicolor* is a perennial **diploid** (2n = 20), which further includes three subspecies, namely, *Sorghum bicolor* (cultivated sorghum) and its nearest wild relatives, *Sorghum arundinaceum* (Desv.) de Wet et Harlan (wild sorghums) and *S. drumondii* (Steud.) de Wet (weedy sorghums) (1-37, 47). Subspecies of bicolor includes all cultivated races and they are further subdivided into basic and intermediate races (1-52). The **five basic races** include bicolor, guinea, caudatum, kafir and durra and the ten intermediate races are those between any two of those types, classified primarily based on grain shape, glumes and panicle (1-44, 47-52).

Majority of the grain sorghum varieties belong to the races **Caudatum, Kafir**, and **Durra**, whereas sweet sorghum and forage sorghum varieties were mainly grouped in the race bicolor (1-47). However, later studies showed that clustering of sweet sorghum lines with other *Sorghum bicolor* genotypes suggesting that sweet sorghum has a polyphyletic origin. Therefore, apart from race bicolor, may have parentage from other previously mentioned races as well (1-47, 48-58). In Africa, where most of the wild germplasm has originated, intermediate varieties are also common. For instance, there are many durra-bicolor intermediates in Ethiopian highlands (1-47-58). Race Kafir has contributed to many intermediate varieties in Tanzania and regions of South Africa (1-47, 48-58).

Sorghum: Botany

Sorghum is considered as a predominantly **self-pollinated** species but with cross pollination occurring to an extent of 4–10 % under specific conditions (1-42, 43-59). Sorghum is a short day plant, and blooming is hastened by short days and long nights (1-52). However, varieties differ in their photoperiod sensitivity (1-59). Tropical sweet sorghum varieties initiated the reproductive stage when day lengths return to 12 h (1-43, 44-49). Inflorescence is a **raceme**, which consists of one or several spikelets (1-44, 47-52). It may be short, compact, loose or open, composed of a central axis that bears whorls of primary branches on every node (1-49, 52). The racemes vary in length according to the number of nodes and the length of the internodes (1-37, 47-59).

Cytoplasmic male sterility has been found in sorghum (A1–A4 systems) which has made possible the development of a **hybrid seed** industry (1-47, 48-59). A good male-sterile plant will not develop anthers, but in some instances dark-colored shriveled anthers with no viable pollen will appear (1-46, 47-59). Partially fertile heads are also observed. Although the anthers frequently have viable pollen, and the quantity is less than in normal plants (1-39, 47-59).

Sweet Sorghum: Breeding methods

According to an estimate, more than **4000** cultivars of sweet sorghum are cultivated all over the world (1-47, 48-52). The breeding methods used for sweet sorghum improvement include introduction, pedigree selection, backcrossing as short-term improvement programs, whereas population improvement has been used as a long-term strategy for simultaneous improvement of economic traits (1-47, 48-59). A collection of **2180** accessions of sweet sorghum in the US National Plant Germplasm System has been served as a source of germplasm for developing varieties in the Mediterranean region and Latin America (47-52). Early **breeding efforts in USA** were concentrated on using sweet sorghum as a sugar crop (1-53). Although several sweet sorghum breeding programs have been initiated in United States. Most of the varieties in cultivation were developed at the U.S. Sugar Crops Field Station at Meridian, **Mississippi** (1-47-58). This breeding program produced four important varieties namely Theis, Keller, Dale, and M81E (47-58). All the four varieties give high yield of syrup per ton of the stalk (1-47).

Recently, Leite and colleagues, evaluated 45 genotypes for association among agro-industrial traits for ethanol yield and prioritized several lines including BR500R, BR505R, CMSXS633R, and CMSXS634R that showed positive association with ethanol yield. Therefore, promising candidates for breeding purposes (47-58). **Inbred lines** are important to ensure availability of genetically uniform individuals with heritable desired traits (like sugar content), which can be further used for the development of elite lines or hybrids (1-52). In hybrid development program, two types of inbred lines are required namely **female inbred lines** (A/B lines) and **male inbred lines** (R lines) (1-47-58). Female inbred lines with high sugar content were released by **Texas A&M University** (1-47-58). The combining ability of the parental lines and hybrids has recently been used to select parental lines for future crossing strategies and screen the hybrids for commercial cultivation (47-59). France, Italy, and Germany are the main centers of sweet sorghum research in European Union (1-47). China is another major center of diversity and producer of sorghum in Asia (1-53). **Chinese sorghum** is also called **Kaoliang** (47). The approaches used for breeding of sweet sorghum cultivars in china are introduction and breeding by selection, utilization of heterosis, cross breeding, induced mutation breeding, and transgenic breeding (1-47).

In 2009, European Union initiated an international project titled "**SWEETFUEL**" that was aimed to improve the sorghum cultivars for better yields (47-52). In addition to European countries, Brazil, India, Mexico, and South Africa were partners in this consortium (1-47). Sorghum bicolor *(L).* is a plant of 1 to 3 meters high, solid cylindrical rod with a terminal inflorescence compact panicle *(1-47-52).* This includes one or two spikelets bisexual flowers (1-53). The seed is a **caryopsis** of about 4 mm (1-52). It produces an upright stem 50 to 70 cm for the present forms cultivated and elongate leaves similar to those of maize (1-53). At the end, develops a panicle of flowers and fruits containing seeds that mature in autumn (1-53). The ideal genotypes would have these two traits combined, i.e., higher biomass with high sugar yields (1-69).

Overall, sweet sorghum improvement programs are motivated by three major goals including (**1**) Improving the quantity and quality of the stalk juice, (**2**) Identification of multipurpose varieties that can accumulate sugars in the stalk as well as produce good quality grains and high biomass, and (**3**) Engineering resistance to combat potential biotic and abiotic stresses. Meeting these goals not only requires extensive germplasm screening but also informed breeding efforts, genetic and genomic resources, optimization of plant transformation and engineering strategies, cross utilization of information from other closely related species, and a well-defined strategy (1-69).

Sweet Sorghum: Research at ICRISAT, Patancheru, Hyderabad, Telangana, India

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Hyderabad, Telangana 502324, India has made the first major attempt in India to evaluate and identify the useful high biomass producing sweet sorghum germplasm from world collections (1-60, 104-148). Sweet sorghum is a promising dry land adapted bio-fuel feedstock that favourably addresses **food-versus-fuel issue** (1-59). Various genotypes of sorghum at ICRISAT gene bank have been divided into seven collections namely 1) Accession collection, 2) Conversion collection, 3) Cultivar collection, 4) Genetic stock collection, 5) Basic collection, 6) Wild Weedy sorghums, and 7) Core collection (1-52). In addition to safeguarding the genetic diversity, ICRISAT makes these accessions freely available to researchers at other institutions (17-26, 47-59).

Sweet sorghum improvement aims for simultaneous improvement of stalk sugar traits such as total soluble sugars or (Brix %), green stalk yield, juice quantity, girth of the stalk and grain yield (1-59). The sweet sorghum program at ICRISAT primarily focuses on developing primarily hybrid parents adapted to rainy and post rainy seasons due to the highly significant interaction of genotype by environment (G x E). During the research work carried out at ICRISAT, about 100 sweet sorghum varieties/ restorer lines and 50 improved hybrids were identified (1-53, 104-148).

Sweet sorghum research at ICRISAT, Patancheru, Hyderabad, Telangana 502324, India was initiated in 1980 to identify lines with high stalk-sugar content in part of the sorghum world germplasm collection maintained at ICRISAT's gene bank initially by chewing the stalks at maturity (1- 59). Seventy accessions that tasted sweet were evaluated during the rainy season of 1980 and nine accessions with high Brix% were planted again in 1981 rainy season, of which two cultivars, IS-6872 and IS-6896, were selected (1-59). Due to changed focus driven by donor perceptions and National Agricultural Research Systems (NARS) needs sweet sorghum research at ICRISAT, Patancheru, Hyderabad, Telangana 502324, India was discontinued in late 1990's (1-59). However, ICRISAT renewed its sweet sorghum research to contribute its share to meet the increased demand created for ethanol following the Indian Government's policy to blend petrol and diesel with ethanol and initiated a program for the identification/development of sweet-stalked and high biomass sorghum hybrid parents and varieties during 2002 (1 -26, 28-59).

In 2011, CSV 24SS another sweet sorghum variety bred by Directorate for Sorghum Research (DSR), Hyderabad was released for cultivation (1-26, 29-59). Thousands of hybrids and segregating populations are under evaluation for stalk sugar traits. Research experience at ICRISAT, Patancheru, Hyderabad, Telangana 502324, India and elsewhere has showed that hybrids produce relatively higher biomass, besides being earlier and more photo-insensitive when compared to the varieties grown under normal as well as abiotic stresses including water-limited environments. Therefore, the development of sweet sorghum hybrids is receiving high priority to produce more feedstock and grain yield per drop of water and unit of energy invested (1-26, 28-59).

The sweet sorghum improvement program during the last two decades at National Research Centre for Sorghum (NRCS), Rajendranagar, Hyderabad 500 030, Telangana, India and the All India Coordinated Sorghum Improvement Project (AICSIP) centers had resulted in the development of a number of breeding lines which led to national level release of 283 several varieties such as SSV 84 (High Brix: 18%), CSV 19SS (RSSV 9) and hybrid CSH 22 SS (NSSH 104) with productivity ranging from 40−50 ton ha^{-1} (1 -59, 104-152). ICRISAT, Patancheru, Hyderabad, Telangana 502324, India has developed a number of sweet sorghum breeding materials, varieties, experimental hybrids having higher stalk sugar content and superior biomass yields (17-26, 27-59, 104-152). Furthermore, ICSV 93046, ICSV 25274, ICSV 25280 and ICSSH 58 were identified for release owing to their superior performance in All India Coordinated Sorghum Improvement Project (AICSIP) multi location trials during 2008–2012 (1-59). Some of the insect and pest resistant materials have been developed at ICRISAT such as ICSR 93034 and ICSV 700 (1 -59, 104-148).

The first sweet sorghum hybrid released in India is CSH 22SS. ICSV 93046 (ICSV 700 9 ICSV 708) is a promising shoot fly, stem borer and leaf diseases tolerant sweet sorghum variety also displays stay green stems and leaves even after physiological maturity and has good grain (3.4–4.1 t ha^{-1}) and biomass yield (1-59, 104-148). The **CSH 22SS is the most popular hybrid of sweet sorghum** that was developed at Indian Institute of Millets Research (IIMR; Formerly known as Directorate of Sorghum Research) IIMR and produce high sugar yields (1-59). It is used as a bench mark for evaluating the performance of new test cultivars (47-59). Under the All India Research Improvement Project (AICRP) on Sorghum, several improved varieties have been released by IIMR and other AICRP centers using pedigree method (1-47, 48-59, 104-148). These include SSV 74, SSV 84, CSV 19SS, and CSV 24SS (1-47, 49-59). Several cultivars and hybrid varieties, that were developed at IIMR and ICRISAT, are being evaluated at national level, while many are ready for commercial cultivation (1-59). At Nimbkar Agricultural Research Institute (NARI), Phaltan, Maharashtra, indigenous germplasm collections (forage and grain varieties) were crossed with exotic lines (American Germplasm) to identify superior germplasm with features like high cane yield and high Brix percentage (1-26, 27-59).

National Research Centre for Sorghum (NRCS), Rajendranagar, Hyderabad 500 030, Telangana, India was in the forefront in organizing pilot studies on sweet sorghum-based ethanol production in collaboration with many distilleries and stakeholders such as Sri Renuka Sugars, Belagavi, Karnataka and Sagar Sugars, Nelavoy, Chittoor, Andhra Pradesh (17-26, 28-59). The alcohol yield realized in these pilot studies was from 25 to 40 liters ton^{-1} of stalks crushed (1-59). Techno-economic feasibility studies have shown that the cost of alcohol production from sweet sorghum was Rs 1.87 less than that from molasses (17-26, 29-59). Recently, NRCS organized pilot studies successfully in collaboration with Sagar Sugars, Chittor, and National Sugar Institute, Kanpur (17-26). ICRISAT, Patancheru, Hyderabad, Telangana 502324, India through its Agri-Business Incubator (ABI) is collaborating with Rusni Distilleries, Sangareddy, Andhra Pradesh and **promoted** sweet sorghum as a biofuel crop. Rusni Distilleries has already started producing ethanol from sweet sorghum (ICRISAT, 2006) (1-59, 104-148).

It is often stated that sweet sorghum cultivars do not produce grain yield or the grain yield is very less vis-a-vis grain sorghum (1-26, 27-59). Studies at ICRISAT, Patancheru, Hyderabad, Telangana 502324, India showed that sweet sorghum hybrids had higher stem sugar yield (11 %) and higher grain yield (5%) as compared to grain sorghum types (1-59, 104-148). Sweet sorghum varieties had 54 % higher sugar yield and 9 % lower grain yield as compared with non-sweet stalk varieties in the rainy season (1-20). On the other hand, both sweet sorghum hybrids and varieties had higher stalk sugar yields (50 and 89 %) and lower grain yields (25 and 2%) in the post-rainy season (1-26, 27-59). Thus, there is little tradeoff between grain and stalk sugar yields in the sweet sorghum hybrids in the rainy season, while the trade off is less in varieties in the post-rainy season (1-26, 27-59, 104-148). The grain and sugar yields are the best in the rainy and summer seasons, whereas in the post-rainy season the grain yield is high, but with less stalk and sugar yield (1-26, 28-59). Rapid sugar accumulation immediately after flowering and its retention for a longer period for staggered feedstock supply is another area of research that deserves immediate attention (1-59). The present day multi-feedstock distilleries can successfully run on a variety of feed stocks like sugarcane, sweet sorghum, cassava and sugar beet etc (1-23, 26-59, 104-148).

Sweet sorghum Research in India

Some parts of the central and southern region, subtropical regions of Uttar Pradesh, and Uttaranchal are the most suitable for commercial cultivation of sweet sorghum in India (1-69, 104-152). Most of the sweet sorghum cultivars available in India have been developed by Indian Council of Agricultural Research (ICAR)–Indian Institute of Millets Research (IIMR; Formerly known as Directorate of Sorghum Research) and All India Coordinated Research Project (AICRP) centers for sorghum (1-46, 47-68). International Crops Research Institute for Semi-Arid Tropics (ICRISAT) has a large repository for *S. bicolor* (L.) Moench and is estimated to have about 80% of the variability present in this crop (1-53). It has a total of 39, 234 accessions from 93 countries (1-47-68).

Sweet sorghum research in India is carried out at Directorate of Sorghum Research (DSR), Hyderabad and at AICSIP centers like Parbhani, Rahuri, Phaltan, Akola (Maharashtra), **University of Agricultural Sciences, Dharwad, Karnataka**, Anakapalli, Perumallapalli, Hyderabad and Palem (Andhra Pradesh), Coimbatore (Tamil Nadu), Surat (Gujarat), Ludhiana (Punjab) and Pantnagar (Uttarkhand) (1-26, 27-59). The Lucknow, UP based Indian Institute of Sugarcane Research (IISR), Punjab Agricultural University (PAU), Ludhiana; Govind Ballabh Pant University of

Agriculture & Technology (GBPUAT) Pantanagar; Tamilnadu Agriculture University (TNAU), Coimbatore; Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri; Marathwada Agricultural University (MAU), Pharbhani and Dr. Panjabrao Deshmukh Krishi Vidyapeeth (PDKV), Akola are also conducting research on sweet sorghum. **Nimbkar Agricultural Research Institute (NARI), Phaltan, Maharashtra** has commercialized sweet sorghum derived syrup, **Madhura** (1- 47-68, 104-148).

Biofuel Production from Plants

Most of the world's ethanol production is obtained from two major crops: **Corn** and **sugarcane** (1-47-69). Sweet sorghum offers one of the best plant-based bio-ethanol productions from its sugary stalk and is considered as a potential bio-energy crop throughout the most of the tropical and temperate zones of the world (1-59). Further, it is also a leading contender for biofuel production in the southern United States (1-68). Apparently, there is an urgent need to explore the sustainable energy sources, which can not only fulfill our energy needs but more importantly mitigate the adverse impact on the environment (1-26, 47-69, 104-148). Biofuels are sustainable and renewable source of energy derived from organic matter in the form of biomass (1-59). Biofuels can be derived from plant as well as animal biomass (1-59, 104-148). Studies showed that plants grown for biofuel purposes have the potential to reduce the **net greenhouse gas emissions** (1-69, 104-148).

Schmer and colleagues reported the usage of **corn and switch grass** as a source of biofuels reduced the greenhouse gas emissions by −29 to −396 g of CO_2 equivalent per mega joule of ethanol per year (1-69, 104-148). Currently, about 2.5% of the world's transportation fuels are produced from the crop plants including **maize, sugarcane,** and **vegetable oils** (1-69, 104-148). However, both maize and sugarcane are input-intensive food crops (1-60, 104-148). Extensive usage of these crops as biofuel feedstock will not only threaten food security but would also compete with other food crops for irrigation and arable land resources (1-62). Therefore, lignocellulosic biomass and plants that can be grown on marginal lands have attracted attention of researchers (1-60, 104-148). In addition to the agricultural waste, several grasses like **switch grass**, ***Miscanthus*,** and **foxtail millet** have been identified as candidate bio-energy feedstock (1-62, 104-148). Another group of plants termed **halophytes** can have a huge impact on biofuel industry as they can grow on coastal areas and would not compete for fresh water resources (1-65, 104-148). An alternate solution to overcome these challenges is to utilize the grasses (for example, sugarcane and sweet sorghum) where sugars, accumulated in the form of juice, can be easily extracted and directly fermented to produce ethanol (1-69, 104-148).

According to the U.S. Department of Agriculture, the ratio of energy invested to energy obtained during biofuel extraction from sweet sorghum is estimated as 1:8 (1-69, 104-148). This ratio may further be improved using engineering and molecular breeding technologies (1-67, 104-148). **Ethanol produced from sweet sorghum is safer for environment due to low sulphur content, low biological and chemical oxygen demand and high octane rating** (1-60, 104-148). Although, annual ethanol output from sweet sorghum depends on several factors including genetic background, time of the year, soil quality, and other environmental factors, sweet sorghum crop is estimated to produce up to 8000 l/ha/year of ethanol (1-56, 104-148).

Sweet sorghum targeted for sugar

Sorghum bicolor has emerged as a promising target for sugar as well as lignocellulosic biofuel production (1-60, 104-148). It has relatively low input requirements with ability to grow on marginal lands (1-59, 104-48). Due to high sugar content and ease of extractability, sweet sorghum is one of the leading feedstock crops for new-age biofuels (1-69, 104-148). In addition to the stem sugars that are major commodity for sweet sorghum cultivation, co-products in the form of grains, bagasse, vinasse, steam, foam, and froth are also utilized as raw material for range of purposes (1-59, 104-148). Syrup obtained from the juice extracted from the stalk of the plant has been used as a sweetener in America since 1890s (1-69, 104-148). In India, the juice is mainly used to make syrup and jaggery though its usage for cooking and lighting fuel has also been explored (1-69, 104-152). **Nimbkar Agricultural Research Institute** (NARI) in rural Maharashtra, India, developed a lantern-cum-stove that uses low-grade ethanol developed from sweet sorghum and provides energy for lightening as well as clean fuel for cooking (1-63, 104-148).

Sugar levels are measured in terms of Brix units

The sugar concentration in **sweet sorghum** stalks is measured **in Brix units**, which represents the percent of soluble sugars (1-59). **One degree Brix is equal to 1 gram of sugar per 100 g of juice** (1-68, 104-148). The Brix content varies in different varieties and also depends on the environmental conditions, internode position, time of the year, and stage of harvesting (1-26, 28-69). Sweet sorghum can accumulate juice up to 78% of the total biomass, whereas the **Brix content** of sweet sorghum has been estimated to range from 14 to 23% (1-69, 104-148). The sugars in sweet sorghum stalks mainly comprise sucrose (~75%) with some amount (~2.6%) of fructose and glucose (1-69). In comparison to lignocellulosic biomass crops like switch grass and *Miscanthus*, soluble sugars in the form of glucose, fructose, and sucrose in sweet sorghum are readily fermentable (1-68, 104-148).

Sweet sorghum: Agronomic Traits

The agronomic traits like short life cycle of about 4 months, ability to grow under adverse environmental conditions, fewer input requirements, low cost of cultivation, and C_4 photosynthesis are especially helpful for its adoption as a biofuel feedstock (1-69, 104-148). Furthermore, **C_4 photosynthesis** is particularly important as it contributes to higher nitrogen and water use efficiency as well as overall robustness of sweet sorghum making it better equipped to survive in the dry regions with higher light intensity/temperatures (1-69, 104-148). Further, sweet sorghum varieties are **taller**, have **larger leaf canopy** surface area, and are equipped with a better light interception and high radiation use efficiency compared to grain and energy sorghums (1-68, 104-148).

Cultivated varieties of sorghum exhibit diverse phenotypic and morphological traits. Based upon the production characteristics and usage, these have been divided into four groups namely; grain, forage, energy, and sweet sorghum (1-59). Grain sorghum varieties are three to six feet tall with large ear heads and primarily serve as food for humans or livestock feed (60-78). The coarse fast-growing forage sorghum varieties are utilized for feed, silage, and grazing (1-60, 104-148). Energy sorghum is specifically bred for high lignocellulosic biomass that can be converted to biofuels, whereas sweet sorghum, also known as sweet stalk sorghum, refers specifically to genotypes that accumulate soluble sugars in the stalk (1-69, 104-148). Sweet sorghum may grow up to twenty feet tall and produce significantly higher biomass yields compared to grain sorghum. Stems of sweet sorghum are thicker and fleshier than the grain varieties, though the seed yield is relatively low (1-69, 104-148).

Sweet sorghum: Biproducts

Value-added chemical production from sweet sorghum not only alleviates dependency and conflict for traditional starch feed stocks (especially corn), but also improves efficient utilization of semiarid agricultural land resources, especially for India (1-59,104-148). Sweet sorghum is rich in components, such as fermentable carbohydrates, insoluble lignocellulosic parts and bioactive compounds, making it more likely to produce value-added chemicals (1-59,104-148). Compared to other agro-industrial feed stocks using *Sorghum bicolor* as a non-food feedstock platform, is a promising candidate for the production of value-added bio-chemicals (1-59,104-152). Based on its genotype traits and usage, so far four groups of *Sorghum bicolor* including grain, forage, fiber and sweet sorghum has been developed and applied (1-59, 104-148). As a non-food feedstock, sweet sorghum contains rich fermentable carbohydrates, insoluble lignocellulosic parts and bioactive compounds, making it more likely to produce value-added chemicals (1-59,104-148). The rich-sugar sweet sorghum juice and insoluble lignocellulosic parts in sweet sorghum bagasse are both the potential raw materials for bio-chemical production either alone or co-fermentation mode (1-60, 104-148). In addition, sweet sorghum is also used to produce some intermediate products, which are further converted to other derivatives, such as **bio-butadien** (1-59,104-148).

For biofuel purposes, juice is fermented to ethanol that can be used as a replacement for conventional fuels (1-59, 104-148). During concentration of juice to syrup, the foam and froth produced can be processed and used to feed livestock or as an organic fertilizer (1-67, 104-148). After juice extraction, the fibrous leftover material, known as bagasse, serves as a raw material for handmade paper, electricity generation, and bio-composting (1-69, 104-148). The lignocellulosic biomass in the form of bagasse can also be used for ethanol production and biodegradable plastics (1-69, 104-148). The silage, derived from bagasse, is rich in micronutrients and minerals and hence, is a nutritious source of animal feed especially for the dairy cattle (1-69, 104-148). Even, the liquid distillate, left after extraction of ethanol from sweet sorghum juice, called vinasse or still age, is also used as a fertilizer in agricultural fields that abates the problem of waste disposal (1-68, 104-148). Other uses of vinasse are anaerobic digestion to produce methane gas for combustion to produce heat energy (1-60, 104-148). The grains of sweet sorghum can also be used as a gluten-free substitute of wheat or corn flour (1-69, 104-148). Although starch reserves in grains can also be used for ethanol and vinegar production; poor quality grain is mostly used for the animal feed (1-69, 104-148).

Sweet sorghum [*Sorghum bicolor* (L.) Moench] is the only crop that provides grain and stem that can be used for sugar, alcohol, syrup, jaggery, fodder, fuel, bedding, roofing, fencing, paper and chewing (1-59, 104-148). It has been used for nearly 150 years to produce concentrated syrup with a distinctive flavour (1-60, 104-148). Sweet sorghums have also been widely used for the production of forage and silage for animal feed (1-59, 104-148). The oil crisis of 1973 and 1976 renewed interest in the commercial production of sweet sorghum for biological transformation into ethyl alcohol for use as fuel or fuel additive (1-50, 104-148).

In general, bio-chemical production from sweet sorghum biomass is of great interest owning to its low-cost and renewability (1-59, 104-148). However, economic competitiveness challenges still exist. Fortunately with the development of efficient technologies, such as synthetic biology, genome editing, catalytic conversion and lignin extraction, sweet sorghum biomass utilization and its products yield and the production economics will be further improved (1-59, 104-148).

Ethanol production from Sweet sorghum

India is one of the fastest growing economies in the world and energy security is critical for its socio-economic development (1-60, 104-148). India's energy security would remain vulnerable until alternative fuels to substitute/supplement petro-based fuels are developed based on indigenously produced renewable feedstocks (1-59, 104-148). **Biofuels** are environment friendly fuels and their utilization would address global concerns about **containment of carbon emissions** (1-59, 104-148). Use of biofuels has, therefore, become compelling in view of the tightening automotive vehicle emission standards to **curb air pollution** (1-69, 104-148). Crops such as **sugarcane and maize** are the main feedstock for ethanol in Brazil and US respectively, while **rapeseed** in Europe and **palm oil** in Malaysia are the main feedstock's for **biodiesel** (104-148). Sweet sorghum is an ideal crop which can be grown in sugarcane growing areas to supplement molasses for ethanol production and also to use the existing sugarcane machinery in the off season (1-59, 104-148). Approximately **4,000 sweet sorghum** cultivars are distributed throughout the world indicating a diverse genetic background to develop regionally specific, highly productive cultivars (1-60, 104-148). Sweet sorghum stalk is used for the production of food grade syrup, alcohol, and even chewed fresh in Brazil and India (1-59, 104-148). With its high sucrose content, the stalk is fermented for the production of bio-ethanol and can yield up to 8,000 L ha^{-1} of ethanol which is approximately twice the ethanol yield of corn and 30% greater than the average produced from sugarcane (1-59, 104-148).

Some sweet sorghum lines attain juice yields of 78 % of total plant biomass, containing 15–23 % soluble fermentable sugar (1-59, 104-148). The sugar is composed mainly of sucrose (70–80 %), fructose, and glucose. Most of the sugars are uniformly distributed in the stalk, with about 2 % in the leaves and inflorescences, making the crop particularly amenable to direct fermentable sugar extraction (1-59, 104-148). The grain stalk juice and bagasse (the fibrous residue that remains after juice extraction) can be used to produce food, fodder, ethanol and power (1-48, 104-148). These important characteristics, along with its suitability for seed propagation, mechanized crop production, and comparable ethanol production capacity vis a vis sugarcane and sugarbeet makes sweet sorghum, a viable alternative source for ethanol production (1-56, 104-148). Sweet sorghum is being widely considered to be suitable biofuel feedstock to a tropical country like India as sugarcane is grown primarily for sugar while corn is used in food and poultry industry (1-59, 104-148). Considering these advantages, sweet sorghum has been emerged as the best alternative feedstock for ethanol production in India (1 -50, 104-148).

Sweet sorghum: Indian National Policy on Biofuels

Sweet sorghum is one of the first generation biofuel feedstock besides sugarcane, sugarbeet and cassava as in the National Bio-fuel Policy (2009) of The Government of India (GOI) (1-59, 104-152). **The Government of India (GOI) approved the National Policy on Biofuels** on December 24, 2009 (1-59, 104-148). The policy encourages use of renewable energy resources as alternate fuel to supplement transport fuels and had proposed an indicative target to replace 20 % of petroleum fuel consumption with biofuels (bioethanol and biodiesel) by end of 12th Five-Year Plan (1-59, 104-148). In a bid to renew its focus and strongly implement the **Ethanol Blending Program** (EBP), the Cabinet Committee of Economic Affairs (CCEA) on November 22, 2012, recommended **5 percent mandatory blending of ethanol with gasoline** (1-69, 104-148). The Government of India's policy is to blend petrol with ethanol (to reduce fuel import bill and environmental pollution) initially up to 5% has triggered production of bio-ethanol from different feed stocks particularly from sweet sorghum (1-59, 104-148). The process of **ethanol production** from **molasses** is highly **polluting as molasses itself as a by-product from the sugar industry** (17-26). Sweet sorghum, similar to grain sorghum, with a potential to accumulate sugars (10−20%) in its stalks as in sugarcane, offers a potential alternative feedstock as cost of feedstock production, water requirement and crop duration is far less than those of sugarcane from which molasses is obtained (1 -26, 27-59, 104-148).

The stillage after extraction of juice from sweet sorghum has higher calorific value and hence can be used to cogenerate power of about 2.5 MW ha^{-1} crop (1-17-26, 27-59, 104-148). Stillage can also be used as animal fodder after suitable processing and also as a substrate for the production of second generation ethanol (17-26, 27-59, 104-148). Further, economics of ethanol production is in favour of sweet sorghum (1-59, 104-148). Per liter cost of production of ethanol from sweet sorghum (Rs 13.11) is lower than that from sugarcane molasses (Rs 14.98). Besides these, use of sweet sorghum will not compromise food security as only stalk juice is used for ethanol production (1-50, 104-148). Ethanol produced from sweet sorghum stalk juice by fermentation and distillation is similar to that produced from sugarcane molasses, but without any **pollution hazards** (1-26, 30-59, 104-152). **Sweet sorghum-based ethanol production** process leaves **no/least hazardous pollutants such as aldehydes** and **sulphur** compared to that based on **molasses (**1-26, 29-59, 104-148).

Sweet sorghum: Commercialization of Ethanol production

Commercial ethanol production commenced at Rusni distillary from June 2007 (1-27, 30-59, 104-152). **Rusni Distillery** was the first sweet sorghum distillery established in the year 2007 near **Sangareddy, Medak district of Andhra Pradesh**, India amenable to use multiple feedstock's for transport grade ethanol production (1-59, 104-148). It has generated 99.4 % of fuel ethanol with a total capacity of 40 kilo liters per day (KLPD) (1-68, 104-148). It also produced 96 % extra neutral alcohol (ENA) and 99.8 % pharma alcohol from agro based raw materials such as sweet sorghum stalks (juice), molded grains, broken rice, cassava and rotten fruits (1-59).

ICRISAT has incubated sweet sorghum ethanol production in partnership with Rusni Distilleries through its Agri-Business Incubator (1-59). Rusni is a 40 KLPD ethanol production unit located in Medak district of Andhra Pradesh (approx. 25 km from ICRISAT headquarters). **It is the world's first sweet sorghum- based ethanol production distillery** (1-59). **Tata Chemicals Limited** (TCL) has started a pilot scale sweet sorghum distillery of 30 KLPD capacity was established in 2009 at Nanded, Maharashtra (1-67). It is used commercially grown sweet sorghum cultivars such as CSH 22SS, ICSV 93046, sugargrace, JK Recova and RSSV 9 in the 25 km radius of the distillery to produce transport grade ethanol and ENA during 2009–2010 (1-60, 104-148). Another centralized distillery "**CF Biotech Ltd"** is in the process of establishing multiple feedstock based distillery in **Gadag district of Karnataka** (1-59). A total of 22 sweet sorghum accessions were tested for 3 years to identify the most promising ones for ethanol production (1-59). S 21-3-1 and S 23-1-1 were found to be the most promising in terms of stalk and grain yields, juice quality and total energy production per unit land area (1-59, 104-148). Three hybrids, **Madhura**, NARI-SSH45 and NARI-SSH48 have been developed at **NARI**, all yield good grain and high brix sweet juice (1-59, 104-148).

Issues with the Ethanol Production at the Distillaries

1. The availability of sweet sorghum stalks for crushing is limited to two seasons and only available for a short period (30–45 days per season) (1-59).
2. The sweet sorghum stalks need to be crushed within 8–12 h of harvesting as sugars start inverting with time delay, which affects juice recovery and fermentable sugar content. This limits the geographical command area of sweet sorghum crop cultivation within a periphery of 50 km radius of the distillery. The farmers beyond this area are not encouraged to take up sweet sorghum cultivation (1-59).
3. As available days for crushing are limited, the entire crop of sweet sorghum stalks pile up at the distillery leading to wastage as the distillery cannot crush more than 900 tons per day (1-50).
4. Crop production is not mechanized to enable comparison of area; so there is no information available on juice quality, its stability and fermentation efficiency (1-59).
5. The productivity of sweet sorghum in post rainy (rabi) (October-November planted) season is 30−35% less than that in rainy (kharif) and summer seasons because of short day length and low night temperatures (17-26, 29-59). In order to meet the industry demand for raw materials, especially during lean periods of sugar cane crushing, there is a need to develop sweet sorghum cultivars that are photoperiod- and thermo-insensitive with high stalk and sugar yields (1-26, 27-59).
6. The large scale cultivation of sweet sorghum can happen if improved cultivars with higher sugar yield with multiple biotic and abiotic stress tolerance are available besides more importantly the policy support from Government of India in terms of both producer and processor incentives materialize (1-59). Owing to its genetic variability in terms of stalk sugar traits such as total soluble sugars, green stalk yield, juice quantity and grain yield, various research institutes in India and abroad have developed superior varieties and hybrids (1-59). Two commercial sweet sorghum based distilleries were established in India but could not operate for long for several reasons. The decentralized crushing units were established to overcome the issues encountered by centralized units (1-59).

Nimbkar Agricultural Research Institute (NARI): Major Achievements

Sorghum (*Sorghum bicolor* (L.) Moench) is a drought-resistant crop and an important food resource in terms of nutritional as well as social-economic values, especially in semi-arid environments (1-59, 91-103). Cultivar selection and processing methods have been observed to impact on composition, functional and nutritional value of sorghum (1-70). Sorghum is one of the major traditional staple food crops in many developing countries. Sorghum represents an important subsistence crop for millions of people in the semi-arid tropics of Africa, Asia and Central America (1-60). This cereal is resilient, and has a good drought, pest resistance, and it is often grown in areas where it is difficult to cultivate other food grains (1-64). Sorghum is widespread, nutritious, easy to grow and well adapted to hot and arid climates. Hence sorghum represents a good crop for exploitation (1-69).

Sorghum is a major grain corn in the world agricultural economy and represents an important staple food for the populations of many developing countries (1-57, 91-103). The cereal is part of the diet of millions of people, representing for them a major source of energy and nutrients (1-60). Sorghum is a valuable grain, due to its content of **protein and micronutrients**, and it is an interesting option for celiac and gluten intolerant people because of the absence of **gluten** (1-59). However, the nutritional value of sorghum as human food, as well as a feed material for food-producing animals, is impaired by the activity of endogenous and exogenous substances (1-56). The former includes an unbalanced amino acidic composition, the presence of cyanogenic glycosides, and anti-nutrients, such as phenolic compounds and phytic acid. The latter includes mycotoxins and heavy metals that jeopardize the safety of the cereal (1-39, 91-103).

Nimbkar Agricultural Research Institute (NARI), is a non-profit (NGO), private organization started to work on sweet sorghum R&D in the early **1970s** (1-59, 91-103). **NARI** institute is situated in Western Indian State of Maharashtra about 300 km Southeast of Mumbai (1-59, 91-103). It is situated in the rural town of **Phaltan** Taluka, Satara District, 300 km Southeast of Mumbai in Maharashtra state (Address: Tambmal, Phaltan-Lonand Road, P.O. Box 44, Phaltan–415523, Satara District, Maharashtra, India). NARI, a NGO was established in **1968** and successfully completed 50 years in 2018 (1-59, 91-103). **Mr B. V. Nimbkar** was the founder of NARI established in 1968. Mr B. V. Nimbkar has started the first private seed company Nimbkar seeds in India in 1964 and established NARI in 1968 (1-59,91-103). Mr. B.V. Nimbkar who remained in the role of President at NARI until 1990. Since then **Dr. Nandini Nimbkar** has held the position of Permanent President. Dr. Anil K. Rajvanshi is currently the director of the institute whereas Dr. Nandini Nimbkar is the president (104-148).

Dr. Nandini Nimbkar was one of the directors of the NARI institute from 1984 to 1990 and has held the position of Permanent President since July 1990. She has nearly 30 years of experience in agricultural research (91-103, 104-148). She has received her B.Sc. in Botany from University of Pune in 1974 and her M.Sc. and Ph.D. in Agronomy from University of Florida, Gainesville, USA in 1978 and 1981 respectively. In 1981, **Dr. Nandini Nimbkar** returned to India to work as a research scientist in the Nimbkar Agricultural Research Institute (NARI) in Phaltan, Maharashtra (1-59, 104-148). The basic philosophy of the NARI Institute has been to solve the age-old problems of rural India through application of excellent science and technology. Consequently, highly innovative research and development work has been undertaken on a small budget in the areas of agriculture, renewable energy, animal husbandry and sustainable development (104-148).

Nimbkar Agricultural Research Institute (**NARI)** has been one of the pioneers who initiated sweet sorghum research in India, and has made a substantial contribution to the development and utilization of sweet sorghum for mainly food and fuel (1-59, 91-103, 104-148). Cultivars developed by the U.S. Sugar Crops Field Station at Meridian, Mississippi, Texas Agricultural Experiment Station, Weslaco and Georgia Agricultural Experiment Station, Griffin were brought to the Nimbkar Agricultural Research Institute during the early 1970's (1-59, 91-103, 104-148). Their major drawbacks were felt to be: (1) Greater susceptibility to pests and diseases than the normally cultivated grain/fodder sorghums in India (2) **Photothermosensitivity** (3) Poor seed quality for human consumption as well as low seed yield and (4) Late maturity (1-59, 91-103). Keeping these shortcomings in mind, a breeding program was carried out to minimize them (91-103, 104-148). As a result NARI was successful in producing relatively early lines yielding about 50 tons of stripped stalks per hectare per season throughout the year (1-59, 91-103, 104-148). The lines were **photothermoinsensitive** and produced medium to bold-sized grain with pearly white color (1-59, 91-103). This was basically achieved by crossing the American lines with M 35-1 or **Maldandi** Jowar as the pollinator (1-60, 91-103**). Maldandi** Jowar is planted locally on a large scale as a fodder/grain variety and has a juicy stalk as well as good quality grain (1-59, 91-103, 104-148).

Grain sorghum is used to be a major locally grown crop. The sorghum variety **Vasant-1** developed by **NARI** gained widespread popularity in Maharashtra and Karnataka in the early 1970s (1-59, 91-103, 104-148). Later in the same decade, NARI for the first time introduced sweet sorghum in India (91-103, 104-148). Since then, the NARI has developed several high yielding varieties with high sugar content (91-103, 104-148). Due to its usage for simultaneous production of grain, sugary juice and animal fodder, **NARI** envisioned sweet sorghum as an excellent multipurpose crop to be grown across the country (1-59, 91-103, 104-148). For producing ethanol from sweet sorghum juice, NARI has set up a solar-powered distillation unit in 1987 (1-59, 104-148). NARI has also developed the end-to-end technology for producing jaggery and syrup from sweet sorghum hybrid '**Madhura**' in the mid-1990s (1-69,91-103). Based on its excellent, anti-oxidant activity and other nutritional qualities, NARI has been popularizing the '**Madhura**' syrup for the last two decades (1-59, 91-103).

Nimbkar Agricultural Research Institute (NARI) has pioneered the development of sweet sorghum after introducing in India in the mid-1970s (1-59, 91-103). Besides syrup and jaggery production, NARI was also the first in India to produce ethanol from sweet sorghum juice developing the complete technology from crop growing to solar-powered ethanol distillation (1-60, 91-103, 104-148). **Madhura** was the **first sweet sorghum** hybrid developed through NARI's breeding program in the early 1990s (1-59, 104-148). Now sweet sorghum has emerged as a potential alternative crop to sugarcane for bio-ethanol production in India (1-59, 91-103, 104-148). A pilot scale testing to determine the suitability and feasibility of using sweet sorghum for ethanol production revealed its usefulness for industrial scale exploitation (1-68, 91-103, 104-148). The experience of commercial scale use of sweet sorghum for ethanol production as tried jointly by ICRISAT and Rusni distillery at Hyderabad was also encouraging (1-59, 104-148).

NARI has developed a sweet sorghum strain NARI-SS-5 (christened as **Madhura-2**) which not only out yielded the released varietal cultivars but also the hybrid cultivar by a considerable margin in kharif (1-59, 104-152). Madhura-2 has also been found to be highly suitable for production under rabi conditions (1-59, 91-103, 104-148). This is especially important as none of the released cultivars are recommended for the production under rabi conditions (1-60, 91-103, 104-148). Thus the development of **Madhura-2** has made it feasible to successfully produce sweet sorghum in both kharif and rabi seasons (91-103, 104-148). Hence making the feedstock available for at least seven to eight months a year if staggered sowing is followed, so that an industrial unit can be successfully operated on it (1-59, 91-103).

American lines were crossed with a local Indian fodder/grain variety to produce varieties with a juicy stalk and good quality grain (91-103, 104-148). Further breeding was carried out to produce varieties and hybrids giving high yield of good quality grain while retaining the characteristic of juicy stalks high in sugar (1-59, 91-103, 104-148). Complete development of indigenous technology for fermentation of sweet sorghum juice, solar distillation of ethanol and finally its use as a cooking and lighting fuel in new and improved stoves and lanterns was carried out (1-60, 91-103, 104-148). The technology of producing jaggery (unrefined sugar) and syrup from sweet sorghum was also developed (1-59, 91-103, 104-148). Consumer response to these products was assessed by marketing them in limited quantities. A completely automated multifuel gasification system capable of producing thermal output between 120-500 KW was developed for direct heat applications such as those in jaggery and syrup making units (1-59, 91-103, 104-148). Sweet sorghum bagasse was also tested in an existing paper mill to assess its suitability for paper manufacture. Areas of possible research for better exploitation of sweet sorghum have been suggested (1-60, 91-103, 104-148).

Since sorghum grain is the staple food grain in the part of India, further improvement in sorghum grain yield was attempted to get a dual-purpose crop giving high yields of grain and stem biomass (1-59, 104-148). To achieve this, crossing was carried out between lines having high stalk yields, **high brix of juice**, property of retention of juiciness of stalk after grain maturity and lines giving high yield of pearly white grain as pollinators (1-60, 91-103, 104-148). This resulted in the production of sweet sorghum varieties capable of giving high yields of grain of acceptable quality and possessing juicy stalks high in sugar (1-59, 104-148). Hybridization was carried out with both non-sweet, dwarf and sweet, tall female lines successfully (1-59, 104-148). Hybrids were generally found to possess greater uniformity and were felt to be more desirable than varieties from commercialization point of view (1-56, 91-103, 104-**148**).

Sweet sorghum: Major pests

Due to high levels of sugars accumulated in the stalks, sweet sorghum attracts several insect pests resulted in heavy toll on overall production (1-59). Major pests of sorghum are the lepidopteran stem borer (*Chilo partellus*) and the dipterans, such as midge (*Stenodiplosis sorghicola*), and shoot fly (*Atherigona soccata*) (1-69). The pests, which specifically affect sweet sorghum and its sugar accumulation, are sorghum midge and midrib panicle-feeding bugs (head bugs) like *Eurystylus oldi* Poppius (1-50). Sorghum plants produce two **antimicrobial compounds** (luteolinidin and apigeninidin), known as phytoalexins that help plants to protect themselves from pathogens (1-26, 47, 74-80). Sorghum is the mostly grown by resource-limited farmers with minimal inputs which is one of the reasons for its low productivity (1-69). The yield and quality of sorghum produce is affected by a wide array of biotic (insect pests and diseases) and abiotic (drought and problematic soils) constraints (1-59, 70-80). The important productivity-limiting constraints are: **shoot fly** (*Atherigona soccata*) (India and Eastern Africa), **stem borer** (*Chilo partellus*) (India and Africa), midge (*Contarinia sorghicola*) (Eastern Africa and Australia) and head bug (*Calocoris angustatus*) [India and Western and Central Africa (WCA)]. Among pests; **grain mold** (complex of fungi predominantly *Fusarium* spp, *Curvularia* spp, *Aspergillus* spp, *Alternaria* spp) (all regions) and anthracnose (*Colletotrichum graminicola*) (WCA and northern India). Among diseases; *Striga* (*Striga asiatica*, *S. densiflora, S. hermonthica*) (all regions in Africa); drought (all regions); and problematic soils – saline (some parts of India and Middle East) and acidic (Latin America) (1-59, 74-80).

Sweet sorghum: Plant Tissue Culture and Genetic Transformation

Genetic transformation and engineering is a promising technology to investigate the gene functions and generate improved cultivars at a rapid rate (61-69). Sorghum is one of the most recalcitrant crops in terms of regeneration capacity and genetic transformation (61-69). However, significant progress has been made in optimizing the regeneration procedures and transformation systems for grain and sweet sorghum in the recent past (61-69).

Sweet sorghum: Genetics

Most of the **genetic mapping** studies in sorghum are based on grain sorghum varieties mainly **BTx623** (1-37, 47, 70). The markers developed include RFLPs (Restriction fragment length polymorphism), AFLPs (Amplified fragment length polymorphism), STS (Sequence-tagged sites), DArTs (Diversity Array Technology), SSRs (Simple Sequence Repeats), SNP (Single Nucleotide Polymorphism), and PAVs (Presence Absence Variations) (1-35, 38-47, 70). Sweet sorghum-specific traits have been evolved several times independent of each other (1-36, 47, 70). These polymorphic marker loci can be used for mapping sugar content-related genes in sweet sorghum (1-26, 38-47, 70). The genome of sorghum is estimated to be ~730 Mb, organized into ten chromosomes (1-26, 47, 70). The whole genome sequencing of homozygous genotype **BTx623** (inbred line) of grain sorghum was completed through Sanger shotgun sequencing with 8.5-fold coverage (1-47, 70). The **whole genome sequencing of sweet sorghum is still awaited** (1-47, 70). Sequencing of two sweet sorghum lines (Keller and E-Tian) and one grain sorghum inbred line (BTx623) to determine genetic variations in their genomes and identified >1 million SNPs, ~99,000 indels, and more than 17,000 copy number variations between sweet and grain sorghums (1-26, 47, 70).

Breeding of sorghum for high and stable yield with improved drought tolerance has received a top priority at ICRISAT (1-59, 74-76). Besides these, traits that are required for adaptation to different sorghum production systems have been considered (1-59, 74-76). **ICRISAT's** partnership efforts with NARS from SAT countries led to the release of 194 improved cultivars over the years (1-59, 74-76). ICRISAT in partnership with national programs in Asia has developed many grain mold resistant varieties (1-59, 74-76). PVK 801, besides being grain mold resistant, is a dual-purpose variety with good quality stover (1-59, 74-76). Varieties such as **ICSV 112** and **ICSV 745** which are high yielding are also foliar disease resistant (ICSV 745 is also midge resistant) (74-76). By using a trait-based breeding approach, ICRISAT has developed several **grain mold resistant** (eg, ICSA 300, ICSA 369, ICSA 400, ICSA 403 and ICSA 404), shoot fly tolerant (eg, ICSA 419 and ICSA 435 for rainy season and ICSA 445 and ICSA 452 for post rainy season), and Cytoplasmic-nuclear male sterility based seed parents (74-76). **Cytoplasmic-male sterility** based seed parents have a good potential for developing **hybrids resistant** to these biotic constraints and thus stabilizing yield gains obtainable from these hybrids (74-76).

Sweet sorghum: Effect of Climate change on growth

The crop improvement research in sorghum needs to be oriented towards genetic, cytoplasmic diversification for high yield and large grain, shoot fly and grain mold resistance, drought and salinity tolerance, post rainy season adaptation, sweet stalk traits and grain micronutrient density (1-59, 74-76). Grain and stover quality needs special attention to enhance the market value (1-59, 74-76). In addition to the biotic and abiotic challenges, presumed climate change affects the sorghum area and its importance globally (1-59, 74-76). Climate change will modify the length of growing period and increases the predicted temperatures across the sorghum growing regions (1-59, 70-79). So, more study is required on the development of drought resistant and heat tolerant cultivars by using modern biotechnology tools (1-59). Similarly, high emphasis would be given for the improvement of post-rainy vintages for increasing the adoption rates in the country (1-59, 74-76). The other emerging areas of sorghum research are development of high yielding sweet stalks, fodder quality and increasing the density of grain micronutrient traits (1-67).

Grain Sorghum (*Sorghum bicolar*): Important staple food

Sorghum is a major cereal in the semi-arid regions of the world where it is an important food and feed crop (50-90). Sorghum species (*Sorghum vulgare* and *Sorghum bicolor*) are the members of the grass family, **Graminaceae** (40-86). Sorghum is known by a variety of names: great millet and guinea corn in West Africa; Kafir corn in South Africa; Dura in Sudan; Mtama in eastern Africa; **Jowar in India**, and Kaoliang in China (70-80). It is usually referred to as milo or **milo-maize in North America** (71). Sorghum is the fifth most commonly used cereal worldwide and is a rich source of many bioactive compounds (60-80). Sorghum, being a **gluten-free cereal** behaves quite differently from wheat and has a poor rheological properties in terms of its pliability, extensibility, and rollability (71).

Indian farmers have a plenty of experience in growing improved sorghum cultivars. In fact, the first sorghum hybrid, **CSH 1**, was released in India in **1964** (35-86). By 1998-99, 71% of the total sorghum area was under improved cultivars (70-80). More than 180 improved sorghum cultivars are now available for cultivation. Often, public and private research institutes in India have developed these cultivars in partnership with ICRISAT (70-80). Improved cultivars, particularly rainy-season hybrids, have many desirable traits such as higher productivity, wider adaptability, short duration, and stature (80-84).

Sorghum is often recommended as a option for farmers operating in harsh environment where other crops do poorly, as it is grown with limited rainfall (400 to 500 mm), and often without application of any fertilizers or other inputs (50-85). In India, nearly 30-40% of the rainy season sorghum grown as a sole crop while the rest cultivated as an intercrop with pulses and oilseeds (50-90). However, around 90 per cent of the post-rainy sorghum grown as a sole crop which is the most preferred for food consumption purpose (60-80).

Sorghum (*Sorghum bicolor*) is the fifth most important cereal crop grown in the world (1-70, 74-76). Sorghum grain is used mainly for human consumption in Asia and Africa while it is used as animal feed in the Americas, China and Australia (74-78). Sorghum is a drought-resistant crop widely spread in tropical regions of the American, African, and Asian continents (50-85). Sorghum (*Sorghum bicolor*) is one of the major cereal crops consumed in India after rice (*Oryza sativa*) and wheat (*Triticum aestivum*) (50-85).

The crop is primarily produced in **Karnataka, Maharashtra**, Telangana, and Andhra Pradesh (74-78). These 4 states together account for close to 80% of the all-India production (40-85). In **North Karnataka**, the main **staple food is sorghum**. India is a major producer of sorghum and other millets. Madhya Pradesh, Gujarat and Rajasthan, Uttar Pradesh are the other states of India producing sorghum (40-88). In India, agriculture is the major source of livelihood for nearly 70 percent of the population and accounts for 28 percent of Gross Domestic Product (50-80). India is the third largest producer of sorghum in the world, and almost entire production of sorghum (95%) in the country comes from the above regions/states (50-81). In India major sorghum producing states are Maharashtra which occupies 49% share in total production followed by Karnataka (21%), Madhya Pradesh (9%), Rajasthan (7%), Andhra Pradesh (4%), Uttar Pradesh (3%) and Gujarat (2%) during 2010-11 (30-99). However, the lion share of total cropped area belongs to Maharashtra (55%) followed by Karnataka (17%), Rajasthan (10%), Madhya Pradesh (6%) and Andhra Pradesh (3%). But, the highest productivity was noticed in Madhya Pradesh (1426 kg per ha) followed by Andhra Pradesh (1213 kg per ha), Karnataka (1180 kg per ha) and Gujarat (1112 kg per ha) during the same period (74-78).

Besides grain, sorghum stover is an important feed in the livestock sector in India for draft and dairy animals particularly in the dry seasons when other feed resources are in short supply (50-85). Hence, dual purpose types that produce both grain and stover are the preferred types (50-90). In the last two decades, the nature and composition of utilization of sorghum grain has undergone a change from staple food to industrial uses such as livestock and poultry feed, potable alcohol, starch and ethanol production (81). Sorghum (*Sorghum bicolor* (L.) Moench) is one of the most important cereal crops widely grown for food, feed, fodder, forage and fuel in the semi-arid tropics of Asia, Africa, the Americas and Australia (50-85). In spite of rapid decreases in the area of sorghum in Asia, the production level has been maintained owing to the adoption of high yielding hybrids (81-82).

In addition to increased overall production levels of sorghum and millet, there have been substantial yield gains in semi-arid regions as well as improved cultivars adopted in some of the poorest areas of India (1-78). The innovations of new, hybrid technology have not been limited to the Green Revolution Crops (50-90). They have also had significant impact on the productivity of small-farmer households growing dry land crops, such as millet and sorghum in India (50-85). Due to the high resistance to drought conditions, it is an ideal alternative to suit the challenges posed by global warming and the drastic dropdown of corn cultivation caused by fallow lands formed over climate changes (50-85). Depending on the color of the pericarp and the endosperm, the crop is classified as brown, black, yellow, white, and red sorghum (50-90). It is required to identify the high-yielding sorghum varieties at the early breeding stage and detected the plants with nutritional deficiencies and microbial contaminations to increase the production (50-86). Accurate predictions of the yield support the cultivators to plan the harvesting, storage, and distribution (1-68).

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and national programs in India, China and Thailand are working on genetic enhancement of sorghum for high yield, grain mold and shoot fly resistance (50-86). In addition, the traits focused at ICRISAT includes post rainy season adaptation encompassing terminal drought tolerance, genetic enhancement for high Fe and Zn contents in grain and sweet stalk traits for ethanol and animal feed production (50-86). Genetic and cytoplasmic diversification of hybrid parents for key traits is critical for sustaining the productivity across different production systems (35-98). The grain and stover quality need special attention in sorghum improvement research to enhance the market value of sorghum (81-82). NARS, ICRISAT and private seed companies are the major stakeholders working for sorghum crop improvement in the last five decades (1960-2012). Altogether more than 256 improved cultivars have been notified and made available to farmers during the same time (80-83).

The USA is a major producer of sorghum, but the grain is not consumed as human food except for a very small fraction, but as animal fodder (50-80). On the other hand, the semi-arid tropics of Africa and India, the sorghum grain forms the staple diet for large populations, where nearly all the produce is used directly as human food (50-86). Studies of the mature sorghum grain structure showed that the embryo constitutes roughly 10%; the bran layers (pericarp) about 8%; and the endosperm more than 80% of the grain (65-75). The relative proportions may vary with genetic background, environment and degree of maturity (71). Sorghum is the most important cereal food crop in moisture deficit areas of eastern Ethiopia (72). It is widely distributed throughout Ethiopia and it is the most important cereal in the lowland areas because of its drought tolerance (72).

Grain sorghum based food products

Sorghum flour is considered as the main alternative for wheat flour, and it exhibits gluten-free nature (74-78). Sorghum is grown for a variety of uses like food, feed, forage and fuel (65-80). However, it is also used for beer, alcohol, starch, sugar, bread and biscuit manufacturing industries (60-80). Sorghum grains constitute the principal source of energy, protein, vitamins and minerals (50-85). Above all, sorghum crop is one among the climate resilient crops that can adapt quickly to climate change conditions (60-86). The demand for gluten-free products has been rapidly increasing in developed countries. In order to develop food products according to market requirements, it is necessary to screen high-quality sorghum plants (50-60). Current **gluten-free market** is dominated by bakery items and the products such as bread, cakes, biscuits, noodles, cereal bars, and pastries are commercially available whereas a number of researches on improving the sensory attributes of sorghum-based products are ongoing (1-68). As a result, several ready-to-eat (RTE) and ready-to-cook (RTC) sorghum based food items are available in the market, such as flakes, pasta, and semolina (50-68). Fast-food consumption is one of the leading causes of diabetes, since sorghum imparts **anti-diabetic** effects. Therefore, fast-food items based on sorghum have become alternatives (50-86). Different processing steps are applied since the range of potential food applications based on sorghum is broad. In the bakery industry, sorghum flour blends are widely used in producing biscuits, cookies, and bread (45-80). Typically, sorghum flour is mixed in a 20%:50% ratio with wheat flour to maintain the products' texture and leavening index (1-59). The blending ratio is determined based on the color of the final product, particle size, the process of baking, the flavor and aroma of sorghum flour (50-67).

The content of chemical compounds in sorghum grain is similar to maize and other cereals (86). Dishes prepared from sorghum varieties with a high tannin content stay in the stomach longer, increasing and prolonging the feeling of fullness (50-86). They are also characterized by a low glycemic index, which is why they are recommended for people with diabetes (50-86). The consumer perception of gluten-free products has already created opportunities for sorghum-based food products to penetrate the market (68-86). Strengthening the market for value-added products based on sorghum motivates the large-scale cultivators in developed countries to deviate from animal feed production to food applications (50-86). As far as the food applications are concerned, the market potential is mainly determined by the low glycemic index and the gluten-free nature of sorghum, which address the current health risks (50-80).

Modern agriculture mostly relies on a small number of crops and varieties selected due to their proneness to intensification, which clearly limits its resilience in a scenario characterized by major changes and challenges (50-89). In contrast, maintaining crop diversity can better preserve soil fertility and reduce the vulnerability of the agricultural system to pests and diseases (60-89). Moreover, diversified diets determine better nutrition and health with direct benefits for human productivity and livelihoods (50-89). Therefore, the food and agriculture sector needs to develop and use adaptive strategies, such as the exploitation and protection of underutilized food resources (50-89).

Sorghum grain: Rheological studies

Rheological studies are one of the most convenient methods for measuring indicators of quality and texture of food products. The rheological properties of dough's describe how they deform, flow or rupture under applied stress and could be used as a tool in the selection and specification of appropriate raw materials (71). Sorghum is less favoured in developed countries owing to its lower nutritive value compared to other cereals (71). Although the absence of gluten makes it highly favourable in the diet of gluten-intolerant populations, which also leads to poor rheological properties (71). Sorghum is a gluten-free cereal and forms the staple diet of a majority of the populations living in the semi-arid tropics (70-90). Sorghum contains various phenolic and antioxidant compounds that could have health benefits, which make the grain suitable for developing functional foods and other applications (60-80). It is usually consumed in the form of bread made from the grain flour. Sorghum dough has poor viscoelastic properties compared to wheat dough and mechanical methods for the production of sorghum roti are scarce (71). However, the properties of dough from a gluten-free cereal like sorghum are more fluid than wheat dough. The rheological properties of sorghum dough have not favoured its being utilized popularly as a source for bread-making (71-80).

Sorghum verities: Kharif and Rabi crop

The sorghum story is complicated by a major shift in production from the rainy season (*kharif)* to the post-rainy season (*rabi)* (50-86). In India, sorghum is grown in two seasons, *kharif* and *rabi* (70-81). As per the data, that of the total food use of sorghum, 50% is accounted for *kharif* sorghum while the rest is from *rabi* sorghum (81). Thus close to 50% of *kharif* sorghum goes for alternative uses. These include demand from animal feed industry mainly poultry and to some extent dairy, alcohol industry, starch industry, food processing and export demand. Further, sorghum grown in *rabi* season would be preferred due to its superior grain quality (50-69). Efforts to increase productivity in case of *rabi* sorghum would help in bringing down the prices of *rabi* sorghum and make it affordable for lower income consumers as they cannot afford to buy ***rabi*** sorghum due to its high price (81).

Changing the consumption preferences among consumers toward wheat and rice rather than coarse grains reduced the demand for both *rabi* and *kharif* sorghum, creating competition (especially for rainy season sorghum) from modern varieties of food as well as cash crops (50-87). *Kharif* sorghum production accordingly declined, despite successful crop improvement efforts by public and private sector breeders (50-85). **Kharif** sorghum yields, however, are steadily increasing, currently at 900 kg/hectare, despite losses to pests and diseases (ergot and mold) (60-86). Production declines in both seasons are evidently mainly driven by reductions in area. The area under *rabi* sorghum, especially in Maharashtra and Northern Karnataka, may not decline substantially and is expected to stabilize at between 4.5 and 5 million ha (50-86).

Rabi sorghum is highly valued as food, because of its excellent grain quality since it is produced during the post-rainy season. It commands higher prices in the market than *kharif* sorghum, often on a par with or higher than (the local durum) wheat (1-67). **Rabi** sorghum is also highly valued as fodder during lean months and is grown without irrigation (60-86). The rabi sorghum stover is also highly valued for its quality. The rabi sorghum stover is much more important than *kharif* sorghum stover, as its harvest precedes the lean summer months (50-86). The economic contribution of fodder to the total income from rabi sorghum is estimated at 45 to 57 percent in varieties and 39 to 47 percent in hybrids in Maharashtra and Andhra Pradesh (NRCS 2007). Thus, even at the low productivity level, rabi sorghum is far more profitable to the producer than kharif sorghum. Both the grain and the stover enjoyed strong demand which may further expand (50-86).

In India, the rainy season sorghum grain is used mostly for animal/poultry feed while the post rainy season sorghum grain is used primarily for human consumption (74-78). The crop residue (stover) after grain harvest is a valuable source of fodder and fuel in India and Africa (70-80). Sorghum also has a great potential to supplement fodder resources in India because of its wide adaptation, rapid growth, high green and dry fodder yields with high **ratoonability** and drought tolerance (74-78). Compared to other major cereals, sorghum requires less water, less external inputs, is more resistant to pests and diseases, and can withstand harsh climatic circumstances (1-60, 70-80). The multi-purpose C_4 crop plays an essential role in food, feed, and fodder security in dryland agriculture (50-59). Grain sorghum is an integral and irreplaceable dietary staple food (77, 78). In Asia, India is the main producer of sorghum despite the crop being mostly cultivated by small and marginal farmers in the stress-prone semi-arid regions (77-78). Additionally, heat, water stress and lack of crop management options accessible and affordable to the farmers contribute significantly to lower the crop productivity (77). Kharif (rainy) sorghum is primarily used for poultry feed, animal feed industries and alcohol whereas rabi (post-rainy) sorghum is grown for household consumption, fodder purposes, fibre, and fuel (50-78). In areas where market linkages for sorghum are poor or limited, and it is mostly a subsistence crop (77, 78). Additionally, new value added/processed food products for human consumption are emerging such as popped sorghum, *papad,* porridge, *rava* and as an ingredient for Indian dishes like *dosa*, *khichdi*, etc which, though in the nascent stage, are likely to be significant avenues for diversifying utilization trends of sorghum (50-86).

Grain sorghum: Climate change

Agriculture is indeed particularly sensitive to climate change. Higher temperatures reduce yields of most food crops, while increasing weed and pest proliferation, while extreme weather events increase the likelihood of crop failures (39-79). Effects are expected to differ widely in different areas of the world (50-86). Furthermore, yield declines for major food crops are expected mainly in the low-income countries, and in particular in Southern Asia. Besides being overall more affected, low income countries are also expected to be less resilient. As a consequence, the food security of a considerable number of people will be put at risk (50-80, 81-89).

Sorghum is an interesting and high potential food resource. Sorghum grains can represent an ideal crop for the sustainability of the agro-food system (60-79). Considering the fast pace of population growth, the effects of climate change on food production, the nutrient depletion of soils and the increasing loss of biodiversity, meeting the global food demand will be a real challenge in the near future (60-80). To be able to adequately feed the world's growing population, the global food sector needs to boost the production or develop adaptive strategies, including the exploitation of underutilized, often neglected, food resources like sorghum (50-86). The aware exploitation and consumption of the many autochthonous landraces, which are well adapted or resistant to adverse conditions and represent an important component of biological diversity, should be highly promoted (88-89).

Grain Sorghum: Phytochemistry

Sorghum, like other cereals is an excellent **source of starch and protein** (70-80). It is a **gluten-free cereal**, which bears significance in the present day scenario where the occurrence of Celiac Disease (CD), an immunological response to gluten intolerance is on the rise (71-86). Sorghum is a valuable nutritional plant, primarily a source of food for humans and a feed for animals (70-86). Therefore, over 35% of the world production of sorghum seeds (estimated at over 60 million tons per year) is the basic nutritional product (70-86). The main ingredient of fully ripe sorghum grains is **starch**. Depending on the variety, 100 g of grains contain 65 to 80 % of starch (70-86). About 60% of these organic compounds are **Caphyrins**—a group of **prolamines** found only in sorghum plants (70-86). The sorghum grains also contain albumin, globulins, and glutelins (70-86). Furthermore, sorghum is a source of polyunsaturated fatty acids for eg.: Linoleic (49%), Oleic (31%), Palmitic (14%), Linolenic (2.7%), and Stearic (2.1%) which (similarly to prolamines) are the main source of kernel storage proteins (70-86).

Bioactive compounds are widely distributed in plant source foods and the most are secondary metabolites (71-89). Sorghum grain is a good source of bioactive compounds (70-73). Grain sorghum contains phenolic compounds like **flavonoids**, which have been found to inhibit tumour development (71). Additionally sorghum is the only dietary source of **3-Deoxyanthocyanidins (3-DXAs**) and even contains the highest amount of phenolic compounds among cereal grains (73). Grain sorghum also contains carotenoids, vitamin E, amines, and phytosterols (73). A wide class of phenolic compounds has been found in sorghum, including phenolic acids, flavonoids, stilbenoids, and tannins (70-73). Numerous phenolic acids had been found in native and processed sorghum grains (73). A number of phenolic acids identified in sorghum has been varied from one study to another study (70-90). Caffeic acid, p-coumaric acid, sinapic acid, gallic acid, protocatechuic acid, p-hydroxybenzoic acid, and ferulic acids have been studied more in the above phenolic acids (71). Further ferulic acid has been found as the predominant phenolic acid (73). Many flavonoids have been found in sorghum grains (73). Sorghum is the only dietary source for **3-Deoxyanthocyanidins** (3-DXAs)(70-80). Luteolinidin (LUT), apigeninidin (AP), 5-methoxyluteolinidin, and 7-methoxy apigeninidin are the four major forms of **3-Deoxyanthocyanidins** (3-DXAs) (73).

3-Deoxyanthocyanidins (3-DXAs) primarily exist in plant tissues as aglycones (73). The sorghum genotype significantly affects the content and composition of **3-Deoxyanthocyanidins (3-DXAs**) in sorghum grain (73). Furthermore, Luteolinidin (LUT), and Apigeninidin (AP) were found higher in red and brown sorghum grains followed by black in comparison to white pericarp sorghum varieties (73). The difference in 3-Deoxyanthocyanidins (3-DXAs) between sorghum genotypes may be attributed to the difference in chalcone synthase and flavonoid-3-O-hydroxylase, which are involved in the biosynthesis of **3-Deoxyanthocyanidins** (3-DXAs). Moreover, 3-Deoxyanthocyanidins (3-DXAs) are present in free forms and stable in solution compared to other ɣ anthocyanidins (73). Hence, **3-Deoxyanthocyanidins (3-DXAs)** are the mostly **water-soluble pigments** in sorghums (73).

Among flavones in sorghum grains, the most well-known compounds are luteolin, apigenin, and naringeninis is the most well-known compound in **flavanones** (73). Additionally, among the class of flavonols, **kaempferol, catechin** and **quercetin** are the most important and catechin is the most investigated flavanols of sorghum grains (70-80). Taxifolin is the most investigated in the di-hydroflavonols of sorghum grains (73). Stilbenoids are a class of substances with a stilbene parent core and a polymer (70-80). Sorghum has the capability of producing stilbenoids metabolites (73). Based on the structural characteristics, tannins can be classified into hydrolysable tannins and condensed tannins (proanthocyanidins) (73). Proanthocyanidins are unique in some cereal grains (70-90). However, there are comparatively more reports about pro-anthocyanidins in various sorghum varieties (70-80). Perhaps the contents of pro-anthocyanidins in sorghum are enough to yield astringency and a bitter taste due to their complexation and precipitation of proteins (71). Hence, **tannins** are considered as the anti-nutrients yet have attracted more attention due to increasing knowledge of their health benefits (73). Carotenoids are C_{40} isoprenoids and have many beneficial effects on human health (73). **Three carotenoids**, lutein, zeaxanthin, and β-caroteneis, are the most investigated in sorghum grains and the main sorghum carotenoids are xanthophylls (lutein and zeaxanthin) (73). The contents of carotenoids have been varied in various studies (73). This may be due to the difference in genotypes, extraction methods, detection methods, and sorghum grain fractions (71). For example, the total carotenoid content varied from 2.12 to 85.46 μg/100 g in one hundred sorghum genotypes (73). Sorghum delivers 24% of Mn, 16% of Cu, 11% of Mg, and 10% of Zn of the recommended daily value (70-80).

The μ-Tocopherol, β-tocopherol, ɣ- tocopherol, and ⱳ-tocopherol are the most studied **toco-chromanols** in sorghum (73). Further, ⱳ-tocopherol was the major toco-chromanol in sorghum, followed by a-tocopherol, and the vitamin E contents (280.7–2962.4 g/100 g in wet basis) in sorghum varied significantly (73). One of the study showed that **β -tocopherol** was the major tocopherol in sorghum and the vitamin E content in sorghum grains differs with different genotypes (73). Therefore, the total content and profile of vitamin E in sorghum varies significantly (73). Amines are the class of low-molecular-mass nitrogenous bases and can be divided into biogenic amines and polyamines (73). The content of bioactive amines in different sorghum lines has been studied and detected (73). The presence of spermine and spermidine were the prevalent amines, followed by putrescine and cadaverine has been detected in sorghum (73). The polyamines represented 60–100% of the total amines in sorghum (73). Therefore, sorghum is a main **source of polyamines** (73).

Phytosterols are the plant-originated steroids. Further β - Sitosterol, campesterol, and stigmasterol have been isolated, and β - sitosterol was found to be the main phytosterol in sorghum grains (73). Policosanols are a class of aliphatic alcohols of high molecular weight and have various bioactivities (70-80). C_{26} policosanol, C_{28} policosanol, C_{30} policosanol, and C_{32} policosanol were isolated and detected. Further C_{28} policosanol was found to be the main policosanol in sorghum (73).

The **starches** and **sugars** in sorghum are released more slowly than in other cereals and hence it could be beneficial to diabetics (71). The largest part of the kernel, the endosperm, is comparatively poor in mineral matter and oil content (70-80). The endosperm contributes mainly to the kernel's protein (80%), starch (94%) and B-complex vitamins composition (50 to 75%) (70-80). The germ fraction of sorghum is rich in minerals and B-complex vitamins and contains over 68% of the total mineral matter, 75% of the oil, and 15% protein of the whole kernel (70-80). Sorghum bran is low in ash, protein and rich in fiber (70-80). Processing removes the outer pericarp, and thus, proportionally increases the protein and reduces the cellulose, lipid, and mineral content of the grain (71-80). The phenolic compounds, carotenoids, vitamin E, amines, and phytosterols have been detected in sorghum grains (73-80). Recently, with the development of new detection technology, new bioactive compounds such as formononetin, glycitein, and ononin have been detected (73). In particular, it is unique compared to other major cereal grains for having various bioactive compounds such as phenolic acids, procyanidins, flavonoids, and anthocyanins (73).

Starch is the principal storage form of carbohydrate in sorghum and the average starch content is 69.5% (71). The carbohydrate composition and structural features of arabinoxylans of sorghum with good *roti* making quality have been evaluated (70-80). Sorghum has similar amounts of starch as wheat flour, but with significantly lower α–amylase (40–50%) and amylolytic (10%) activity when compared to wheat flour (71). Proteins form the second major component of sorghum grains (70-80). The protein content of sorghum is affected by both genetic and environmental factors (71).

High fiber content and **poor digestibility** of nutrients is a characteristic feature of sorghum grains, which severely influences its consumer acceptability (70-80). Sorghum cultivars have been proven to have reduced **amounts of lysine, threonine** and **total sulphur amino acids** (71). The nutrient composition of sorghum is at par with wheat and rice, but the protein quality is poor due to its **high leucine and tannin contents** (71). Hence, it would be beneficial to incorporate other cereal or legume flours to enrich its nutritional quality (71). Sorghum grain has been reported to have the lowest raw starch digestibility due to restrictions in accessibility to starch caused by endosperm proteins (71). The presence of **tannins** in the grain contributes to the **poor digestibility of starch** in some varieties of sorghum (70-80). **Tannins** isolated from sorghum grain were shown to inhibit the enzyme X-amylose, and they also bind to grain starches to varying degrees (71). The low starch digestibility has also been attributed to a high content of dietary fibre (71). It is indicated that starch digestibility in cooked sorghum flour has been attributed to the formation of **disulphide bonds** during cooking, which leads to toughening at the surface and interior of protein bodies (71).

Sorghum has a higher crude **fat content** (3%) than wheat or rice (71). The germ and aleurone layers are the major sources of the fat content (70-80). The germ contributes to about 80% of the total fat (71). The mineral composition of sorghum grains is highly variable (70-80). Sorghum is a rich source of **B-complex vitamins**. Other fat-soluble vitamins, namely D, E, and K, have also been found in sorghum grain (70-80). **Sorghum is not a source of vitamin C** (71). The concentrations of thiamin, riboflavin, and niacin in sorghum were comparable to those in maize (71). **Sorghum does not contain vitamin A**, although certain yellow endosperm varieties contain small amounts of ***β*-carotene**—a precursor of vitamin A (71). Cellulose, the major insoluble fibre component of sorghum varied from 1.19 to 5.23% in sorghum varieties (71). Grain sorghum does contain phenolic compounds other than tannin that affect its sensory and nutritional quality (71, 73).

The bioavailability of iron in sorghum is negatively affected by the presence of polyphenols and phytates (70-80). The germination, malting and fermentation increases the nutritional value of sorghum by causing significant changes in its chemical composition and the elimination of **anti-nutritional factors** (71). Apart from essential macronutrients, vitamins, and minerals, the sorghum grain also contains **anti-nutritional substances** (71). They are essential for many biological processes in plants. On the other hand, they have **some negative effects** on the organism of humans and animals (70-80). One of the groups **of anti-nutrients found in sorghum are phenolic compounds**, including **phenolic acids and flavonoids** (70-89). Some sorghum grains contain condensed polyphenols called tannins in a layer under the seed coat, but the most cultivated sorghum plants do not contain them at all (70-89). Tannins protected the sorghum grain from insects and birds, but also inhibit certain enzymes (71). As a result, **the digestibility of the protein** and the degradation of cellulose are difficult (86-87).

Grain Sorghum: Health benefits

Sorghum is an increasingly important cereal food with important health-promoting properties. It is an important source of bioactive compounds, such as 3**-Deoxyanthocyanidins** (50-85). Multiple *in vitro* and *in vivo* studies have shown that sorghum grains have extensive bio-logical activities, such as **antioxidative, anticancer, antidiabetic, anti-inflammatory,** and **antiobesity** properties (50-73). Sorghum phenols have been shown to act as antioxidants in vitro (71-86). **Antioxidants** have been reported to be able to decrease the risk of several diseases including **cancer, atherosclerosis, rheumatoid arthritis, inflammatory bowel disease,** and **cataracts** by lowering the amount of **free radicals** (70-80). They can also be used as antifungal, antibacterial, and antiviral agents (50-71). Multiple studies have shown that bioactive compounds in sorghum grains can benefit the **gut microbiota** and have extensive biological activities, such as anti-inflammation, antioxidation, antithrombotic, and antidiabetic properties (73, 87). It is **gluten-free** and drought-tolerant among major cereal grains (73). Grain sorghum contains phenolic compounds like **flavonoids**, which have been found to inhibit **tumour** development (70-80).

There are several diet-related chronic diseases (e.g., diabetics, heart disease, obesity, and cancer), and therefore, specifically **plant-based nutrition** is expected to be increasingly important worldwide for prevention and control of these diseases (50-86). Furthermore, sorghum varieties that seem to hold promise for mitigating rising CO_2 stress as well as malnutrition (50-125). One of the study also provided an opportunity for future genetic studies to further efforts in bio-fortification efforts of sorghum (50-87). In addition, sorghum is an excellent **bulking agent** than wheat, and it possesses cholesterol-lowering ability (50-86). The rich profile of antioxidants, including phenolic acid, flavonoids, and so on makes sorghum appealing for the food industry (50-86).

Sorghum does not contain **gluten**, and it is also a rich source of antioxidant compounds other than vitamins or macro- and microelements, including phenolic acids, flavonoids, and sterols (50-

85). **Phytosterols** such as beta-sitosterol, campesterol, and stigmasterol were found in all the analyzed products (59-80). Based on experimental research, it was investigated that the products containing sorghum grains can be classified as functional food (50-85). Additionally, sorghum is a rich source of antioxidant compounds such as vitamins or macro- and microelements, including phenolic acids, flavonoids, and sterols (50-86). Several studies conducted by scientists have shown that sorghum works against **obesity** (86). The experimental results showed that the extracts of this cereal significantly inhibited the differentiation and accumulation of **triglycerides** (50-86). Characteristic for the protein composition of this grain is the lack of gluten, and its grains are low in lysine (50-86).

Sorghum is a good source of fiber, especially the insoluble fraction. This fiber can shorten the time it takes for food to pass through the digestive system and prevent gastrointestinal problems (50-85). Protein content and composition vary with genotype, water availability, temperature, soil fertility, and environmental conditions during grain development (50-86). The protein content in sorghum is usually 11–13% (50-86). The main protein fractions in sorghum are **prolamines** and **glutelins** (50-80). The amount of soluble sugars, pentosans, cellulose, and hemicellulose are low (50-87). Sorghum is a good source of fiber, especially in the insoluble fractions (86). Therefore, **polyphenol** and **catechin** contents can be used as bio fingerprints to sort sorghum cultivars suitable for **heart patients** (50-86). Thus, a range of value-added products with therapeutic properties can be developed and it facilitates market penetration. Therefore, sorghum cultivation can be improved and diversified to cater to the demands of specific customer segments (90).

Grain sorghum: Anti-Nutritional Properties

Sorghum also contains phytic acid, phytates that form complexes with minerals such as calcium, iron, and magnesium, making them biologically inaccessible for absorption (50-86). Studies have shown that **sorghum bran** contained the highest levels of phytates (86). The last group of anti-nutritional substances are **Cyanogenic glycosides**, the representative of which, i.e., **Dhurrin**, is present mainly in the leaves and germinating seeds of sorghum (50-86). When germinating seeds are processed, **Cyanide**, which is a very **toxic substance** can be released (50-85). The lethal dose of **Dhurrin** in humans is very high, and sorghum contains little of it (50-86). Consequently, a person would have to **eat a significant amount of raw sorghum to experience the negative effects** (50-85). The nutritional value of sorghum as human food, as well as a feed material for food-producing animals is impaired by the activity of endogenous and exogenous substances (50-85). The former includes an unbalanced amino acidic composition, the presence of cyanogenic glycosides, and **antinutrients,** such as phenolic compounds and phytic acid (50-80). The latter includes **mycotoxins** and **heavy metals** that jeopardize the safety of the cereal (50-89).

Grain sorghum: Quality traits detection methods

Sorghum or **Jawar** (*Sorghum bicolor*) is predominantly grown in the arid and semi-arid regions of India (**Karnataka**, Maharashtra, Andhra Pradesh, Telangana, and Tamil Nadu) (50-85). As many as 100 distinct cultivars of sorghum have been identified in the sorghum-growing regions of India (50-85). **India** is the unique center of origin for the post-rainy (Rabi) season varieties of sorghum (50-85). The food products based on sorghum are rapidly becoming popular among health-concerned consumers due to their gluten- and allergen-free nature (50-90). Therefore, food product development from sorghum flour needs to be further enhanced with the novel processing techniques (50-90). The availability of different sorghum strains with contrasting nutritional and color profiles is a challenge to screen favourable cultivars (49-90). The application of conventional methods encounters many limitations. Spectroscopic platforms have been developed as a rapid and non-destructive tools (59-90).

In order to screen nutritionally rich sorghum, there should be a measuring procedure, and the analyses are categorized as chemical and physical methods (90). On the approach of screening the best sorghum, conventional methods encounter many challenges and limitations (90). **Antioxidants** are analyzed qualitatively and quantitatively (90). The total antioxidant content and antioxidant activity are measured by spectrophotometric means by evaluating the free radical scavenging capacity of sorghum grain and sorghum bran (59-90). Similarly, high performance liquid chromatography (HPLC) is commonly used for analyzing individual phenolic acids, flavonoids, alkaloids, and tannins (50-90). The esters present in sorghum impart aromatic properties and volatile compounds are identified and quantified through gas chromatography-mass spectroscopy (**GCMS**), which is applicable for both raw and cooked forms of sorghum (90). Physical methods of analysis also contributed significantly to screen the best sorghum as physical parameters correlated with the chemical composition of sorghum (50-90). For instance, the color of the pericarp and endosperm, size, hardness, and shape of the grains impact the chemical composition of sorghum (50-90). Apart from the endosperm composition, the brain structure determines the flour's color, volume, and texture (90).

Wet chemical methods for proximate analyses required large sample sizes, are labour intensive, and usually take around 1–2 weeks to deliver the results from accredited laboratories (50-90). The sophisticated instrument-based methods like **HPLC, LC-MS, and GC-MS** needs skilled analysts, are time consuming on chromatographic separations, and expensive standards are essential for identifications and quantifications (50-90). Generally, spectrophotometric methods are followed by pre-treatments, prolonged sample extractions, purifications, and dilution preparations utilizing large solvent volumes (89-90). Conclusively, traditional assays are currently used for the analysis of sorghum are restricted by time, labour, and technology, forcing scientists to look for alternatives (50-90). However, the quantifications are based on calibration curves, and therefore the readings should be further validated with reference samples and existing conventional methods to deliver more accurate and reliable predictions (50-90). As a remedy to overcome the drawbacks of conventional methods, rapid screening tools have been introduced (50-90). Various types of spectroscopic methods such as **Fourier Transform Infrared (FTIR), Near Infrared (NIR),** and **Nuclear Magnetic Resonance (NMR**) **spectroscopy**, are becoming popular as rapid tools (50-90).

CONCLUSION

This literature review paper highlights both grain sorghum and sweet sorghum as a food, animal feed and bio-ethanol production. Sorghum is a major cereal in the semi-arid regions of the world where it is an important food and feed crop. **Sweet sorghum bagasse** is a cheap, widely available resource. It is used as an alternative material for the ethanol production. Sorghum species (*Sorghum vulgare* and *Sorghum bicolor*) are the members of the grass family, *Graminaceae*. Sorghum have been considered to be a highly potential source of food, feed and fuel, especially sweet stalk sorghum that posses both functions as a source of food from its grain and fuel made from its stalk juice. The food products based on sorghum are rapidly becoming popular among health-concerned consumers due to their **gluten- and allergen-free** nature. Sorghum also has a great potential to supplement fodder resources in India because of its wide adaptation, rapid growth, high green and dry fodder yields with high **ratoonability** and drought tolerance.

Sorghum grains have a extensive bio-logical activities, such as **antioxidative, anticancer, antidiabetic, anti-inflammatory,** and **anti-obesity** properties. Therefore, grain sorghum has been considered as one of the functional food and staple food in North Karnataka, Maharashtra, Telangana, Andhra Pradesh states of India, China, America, Europe, Australia and Africa. An additional relationship was observed between the content of health-promoting ingredients and the percentage of sorghum in products. Whole grain products, including sorghum, are richer in bioactive ingredients due to the accumulation in the outer layers of the grain. Based on experimental research, it was found that the products of processing sorghum and those containing sorghum grains can be classified as functional foods.

The demands for alternative sources of energy are currently growing because people now are more aware of the many negative impacts fossil fuel gives to the environment. Plant based renewable energy provides potential sources of energy with advantages of cleaner fuel effect and capability of integration with food crop production. Sweet sorghum (*Sorghum bicolor* [L.] Moench), which later can be divided into grain sorghum and sweet stalk sorghum are highly water efficient crop that requires low amount of water intake for its biomass growth and grain production. It can be cultivated on marginal land, mainly drought prone areas where other crops cannot survive. The morphology of sweet sorghum is relatively different from grain sorghum, which is generally have taller plant height and possessed high biomass. Furthermore, stalk of sweet sorghum produces juice that has high sugar content, which can be used as a main source of ethanol production, whereas grain of sorghum can also be used as raw materials for food, feed and functional food. Beside for bio-ethanol, sorghum grain and juice can also be used to produce other kind of industrial products such as bio-plastic, beverages and also syrup.

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