Series of Crop Specific Biology Documents

BIOLOGY OF *SORGHUM BICOLOR* (SORGHUM)

Phase II
Capacity
Building
Project on
Biosafety

सत्यमेव जयते

UNEP

gef

भाकृअनुप
ICAR

भा कृ अनु सं
IIMR
Hyderabad

प्रकृतिः रक्षति रक्षिता
Nature Protects if She is Protected

Ministry of Environment, Forest and Climate Change
Government of India

Series of Crop Specific Biology Documents

BIOLOGY OF *Sorghum bicolor* (SORGHUM)

Phase II Capacity Building
Project on Biosafety

Ministry of Environment, Forest and Climate Change
Government of India

Biology of *Sorghum bicolor* (Sorghum)

Prepared by :
Ministry of Environment, Forest and Climate Change (MoEF&CC)
and Indian Institute of Millets Research, Hyderabad
under UNEP/GEF supported Phase II Capacity Building Project on Biosafety

Complied by:

Dr. D. Balakrishna
Principal Scientist
Indian Institute of Millets Research,
Hyderabad

Dr. B. Venkatesh Bhat
Principal Scientist
Indian Institute of Millets Research,
Hyderabad

Reviewed by:
Dr. Ranjini Warrier
National Project Coordinator, Phase II Capacity Building Project on Biosafety
Advisor, MoEF&CC

Dr. O. P. Govila
Former Professor of Genetics, Indian Agriculture Research Institute

Dr. Michael Wach
Senior Scientist, Program Manager,
Centre for Environmental Risk Assessment-ILSI Research Foundation

Dr. Vibha Ahuja
Chief General Manager, Biotech Consortium India Limited (BCIL)

Consultation:
The inputs and comments provided by the following institutions are gratefully acknowledged.

- Chaudhary Charan Singh Haryana Agricultural University, Hisar
- Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur
- Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani
- Dr. B S Konkan Krishi Vidyapeeth, Dapoli
- S K Rajasthan Agricultural University, Bikaner
- University of Horticultural Sciences, Bagalkot
- Maharashtra Hybrid Seeds Co. Ltd., Mumbai

Assisted in co-ordination & printing by:
Dr. P. Hareesh Chandra, Project Consultant and Ms Sonia Kaushik, Senior Project Executive, BCIL
Project Coordination Unit, Phase II Capacity Building Project on Biosafety

For further information, please contact:
Ministry of Environment, Forest and Climate Change
Government of India
Indira Paryavaran Bhawan
Jor Bagh Road, Aliganj
New Delhi 110003
Email: biosafety-mef@nic.in

प्रकाश जावडेकर
Prakash Javadekar

राज्य मंत्री (स्वतंत्र प्रभार)
MINISTER OF STATE (INDEPENDENT CHARGE)
पर्यावरण, वन एवं जलवायु परिवर्तन
ENVIRONMENT, FOREST & CLIMATE CHANGE
भारत सरकार / GOVERNMENT OF INDIA

Message

I am happy to learn that the Ministry of Environment, Forest & Climate Change (MoEFCC) as part of the initiative under the UNEP GEF supported "Phase II Capacity Building Project on Biosafety" has developed eight crop specific biology document on Chickpea, Mustard, Papaya, Pigeon-pea, Potato, Rubber, Sorghum, and Tomato.

I am happy to note that the documents have been prepared with support from seven research institutions namely Indian Institute of Pulses Research, Directorate of Rapeseed and Mustard Research, Indian Institute of Horticulture Research, Central Potato Research Institute, Rubber Research Institute of India, Indian Institute of Millets Research and Indian Institute of Vegetable Research.

While Bt cotton is the only genetically modified (GM) crop approved for commercial cultivation in India, there are several crops under various stages of research, development and field trials. The present set of crop specific biology documents aims to provide scientific baseline information of a particular plant species that can be used as credible source of information for conducting safety assessment of GM plants.

I would like to congratulate all those who were involved in preparing these documents and those involved in steering this initiative.

I am confident that these biology documents will serve as a valuable tool for regulators, scientists, crop developers, policymakers, academicians and other stakeholders who are involved in the safety assessment of GM plants. I am also hopeful that baseline information provided in the biology document would further enhance awareness on biosafety aspects of GM crops.

(Prakash Javadekar)

Paryavaran Bhawan, Jor Bagh Road, New Delhi-110 003
Tel.: 011-24695136, 24695132, Fax : 011-24695329
www.youtube.com/prakashjavadekar www.facebook.com/prakashjavadekar
www.twitter.com/prakashjavadekar e-mail :mefcc@gov.in
website : www.prakashjavadekar.com

Hem Pande
Special Secretary &
Chairman, GEAC

भारत सरकार
पर्यावरण, वन एवं जलवायु परिवर्तन मंत्रालय
GOVERNMENT OF INDIA
MINISTRY OF ENVIRONMENT, FORESTS AND CLIMATE CHANGE
इंदिरा पर्यावरण भवन, जोर बाग रोड,
नई दिल्ली-110 003
INDIRA PARYAVARAN BHAWAN, JOR BAGH ROAD,
NEW DELHI-110 003
Website : moef.nic.in

सत्यमेव जयते

PREFACE

India is an agriculture based economy with abundance of genetic base, diverse agro-climatic zones and highly qualified manpower which provides a rich scope for technological advances in agricultural biotechnology. The shortage of healthy seeds/planting material, lack of disease resistant clones, crop damage by insects, pests etc. have often affected the Indian agricultural economy adversely and therefore the role of new technologies assumes significant importance for Indian economy.

With significant advances in the field of agricultural biotechnology the regulatory system has to deal with multiple crops integrated with multiple traits. In order to streamline the process of safety assessment, the Ministry of Environment, Forest & Climate Change (MoEF&CC) under the UNEP-GEF supported "Phase II Capacity Building Project on Biosafety" has prepared a set of crop specific biology documents namely Chickpea, Mustard, Papaya, Pigeon-Pea, Potato, Rubber, Sorghum, Tomato with support from six Indian Council of Agriculture Research (ICAR) institutions and Rubber Research Institute of India.

The biology documents provides an overview of baseline biological information of a particular plant species such as taxonomy, the centres of origin, its related species including wild relatives, general description of their morphology, reproductive biology, biochemistry, potential for gene introgression, biotic and abiotic interactions. Such species specific information is expected to serve as a guiding tool for use in risk assessment of genetically modified (GM) plants.

The documents has been prepared through a consultative approach and comments received from several organizations have been extremely useful in validating this

document. I express my deep appreciation for the support provided by Indian Institute of Pulses Research, Directorate of Rapeseed and Mustard Research, Indian Institute of Horticulture Research, Central Potato Research Institute, Rubber Research Institute of India, Indian Institute of Millets Research and Indian Institute of Vegetable Research in preparing these documents. I would also like congratulate Dr. Ranjini Warrier, Advisor, (MoEFCC) and Dr O.P Govila (Former Professor, Department of Genetics, IARI) for their sincere efforts and the consultative approach adopted in finalizing the biology documents.

I am confident that these crop specific biology documents would be of immense value for researchers, regulators and industry in planning for the safety assessment of GM crops.

Hem Pande

CONTENTS

BIOLOGY OF *Sorghum bicolor* L. MOENCH (SORGHUM)

1. INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is a plant belonging to the family of grasses (*Poaceae*). Sorghum, a C4 grass that diverged from maize around 15 million years ago, is the fifth most important cereal grown worldwide (Dogget, 1988). Sorghum is well adapted to tropical and subtropical climates, but the greater part of the area of the crop falls in drought-prone, semi-arid tropical regions of the world. In these harsh environmental conditions sorghum is predominantly grown for human consumption followed by animal feed and fodder. Sorghum could also play an important role in its alternate uses in brewing industry for the production of ethanol, starch and syrup. The global area under sorghum cultivation is estimated at 42.12 million hectares, and the production of sorghum has been estimated to be at the level of 61.38 million tonnes (Fig. 1; FAOSTAT, 2013). India stands second globally for the area under sorghum cultivation (6.18 million hectares) and its production (5.28 million tonnes).

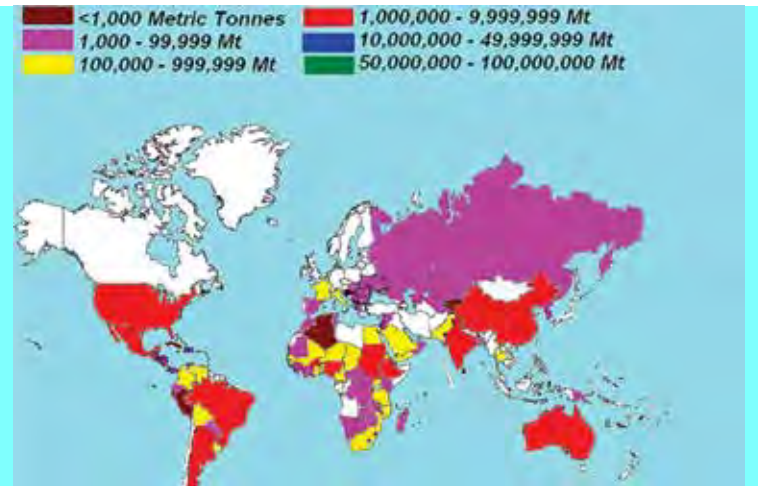


Fig.1: Global sorghum production map (**Source:** FAO statistics)

1.1 Classification and Nomenclature of Sorghum

Sorghum was first described by Linnaeus (1753) under the name *Holcus*. Adanson used the name Sorghum as an alternative for *Holcus*. Moench later separated the genus *Sorghum* from genus *Holcus* (Clayton, 1961; Table 1).

Table 1. Taxonomic position of *Sorghum bicolor* subsp. bicolor

Taxonomic rank	Latin name
Kingdom	*Plantae*
Division	*Magnoliophyta*
Class	*Liliopsida*
Order	*Cyperales*
Family	*Poaceae*
Genus	*Sorghum*
Species	*Sorghum bicolor*

(**Source:** www.graminae.org)

Celarier (1959) divided into five subgenera (Fig. 2): *Sorghum, Chaetosorghum, Heterosorghum, Parasorghum, and Stiposorghum. Parasorghum* includes five species (*S. grande, S. leiocladum, S. matarankense, S. nitidum, and S. timorense*), *Stiposorghum* contains 10 species (*S. amplum, S. angustum, S. brachypodum, S. bulbosum, S. ecarinatum, S. exstans, S. interjectum, S. intrans, S. plumosum and S. stipoideum), Chaetosorghum (S. macrospermum)* and *Heterosorghum (S. laxiflorum)* are monotypic (Lazarides *et al.*, 1991).

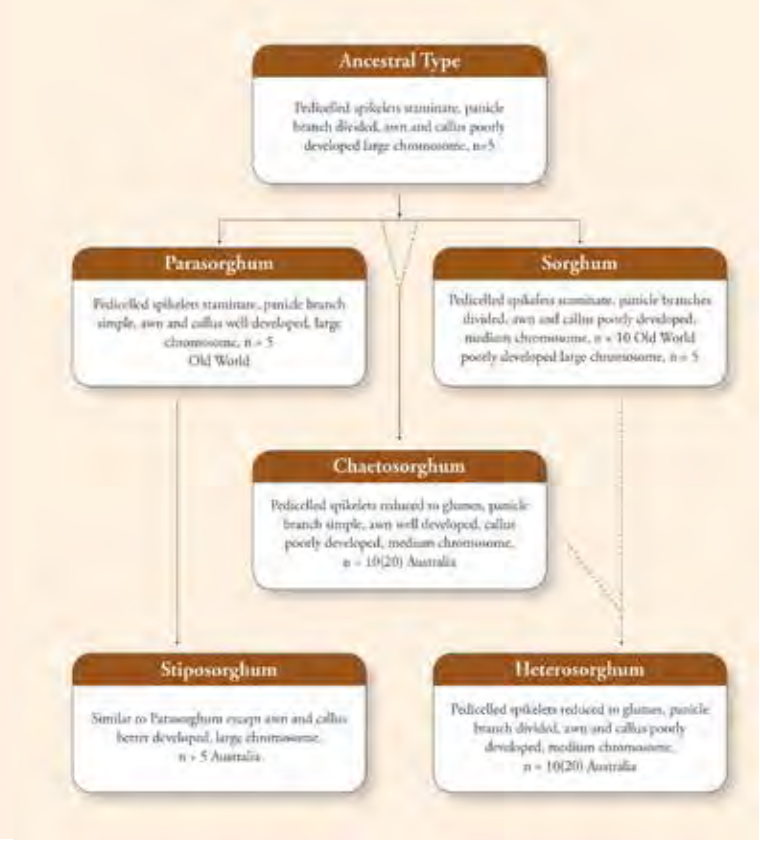


Fig.2: Hypothetical relationship among subgenera in the genus *Sorghum*

Harlan and de Wet (1972) and de Wet (1978) further classified and recognized three species in the subgenera *Sorghum (S. halepense, S. propinquum*, and *S. bicolor*) representing all annual wild, weedy and cultivated taxa. *S. bicolor* further divided into three subspecies *S. bicolor* subsp. *bicolor, drummondii and verticilliflorum* (de Wet, 1978; Mann *et al.*, 1983). *Sorghum halepense and Sorghum propinquum* are wild sorghums, and *Sorghum bicolor* subsp. *drummondii* and *verticilliflorum* are annual weeds.

Sorghum bicolor subsp. *bicolor* contains all the cultivated sorghums. Dogget (1988) described as annual plants. Harlan and de Wet (1972) classified further into five major races are *bicolor, guinea, caudatum, kafir and durra* (Fig. 3) and 10 intermediate races are *guinea-biclor, caudatum-bicolor, kafir-bicolor, durra-bicolor, guinea-caudatum, guinea-kafir, guinea-durra, kafir-caudatum, durra-caudatum* and *kafir-durra*.

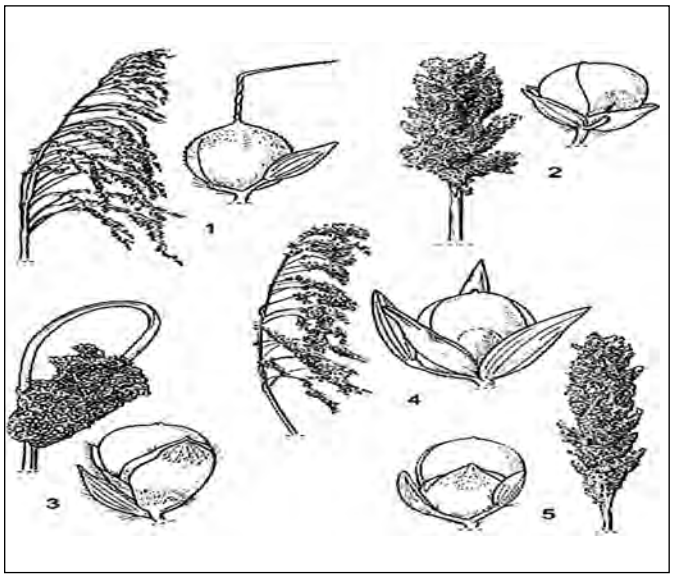


Fig.3: Panicles and spikelets of the five basic races of sorghum 1) *Bicolor*, 2) *Caudatum*, 3) *Durra*, 4) *Guinea*, 5) *Kafir* (**Source:** PROSEA)

1.2 General Description of *Sorghum bicolor*

Sorghum is an annual plant, monoecious, tall, with one to many tillers originating from the base or stem nodes. Roots are concentrated in the

top of the soil but sometimes extending to twice that depth, spreading laterally. The stem (culm) is solid, usually erect; leaves alternate, simple, long leaf sheath often with waxy bloom with band of short white hairs at base near attachment and articulated, ligule short, blade lanceolate or linear-lanceolate, initially erect later curving, margins flat or wavy (Fig. 4).

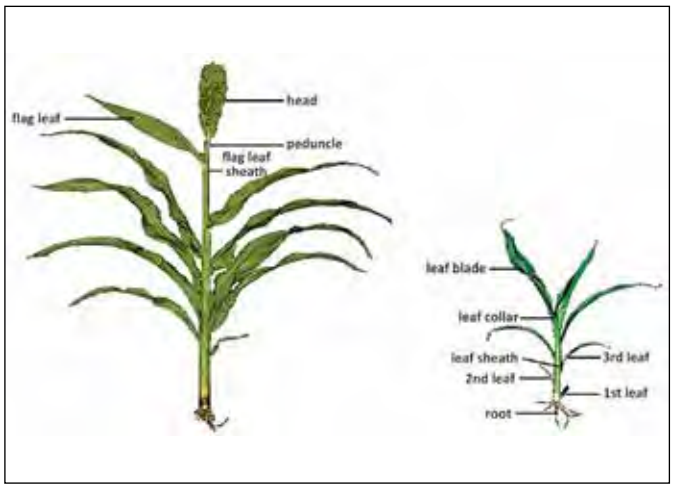
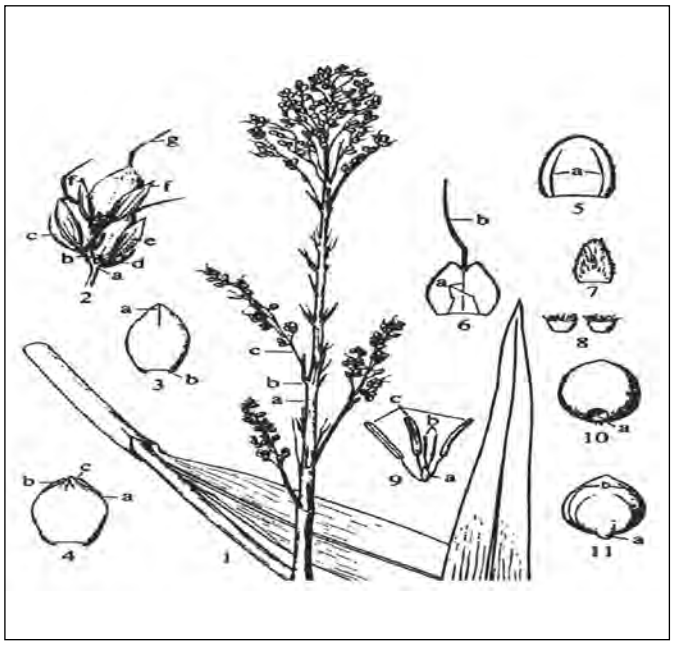


Fig.4: Sorghum plant and its components (**Source:** www.soilcropandmore.info)



Inflorescence is a terminal panicle comes out of flag-leaf sheath at heading time. Panicle is long, compact or loose, open. Rachis is short or long with primary, secondary, and sometimes tertiary branches with spikelets in pairs and in groups of three at the ends of branches. Spikelet is sessile and bisexual or pedicelled and male or sterile with 2 florets; sessile spikelet is long with glumes approximately in equal length, lower glume is veined usually with a coarse keel-like vein on each side, upper glume usually narrower and more pointed with central keel for part of its length, lower floret consisting of a lemma only, upper floret bisexual with lemma cleft at apex, with or without kneed, twisted awn, palea when present is small and thin, 2 lodicules, 3 stamens, ovary superior, 1-celled with 2 long styles ending in feathery stigmas. Pedicelled spikelet is persistent or deciduous, smaller and narrower than sessile spikelet, often consisting of only two glumes, sometimes with lower floret consisting of lemma only and upper floret with lemma, 2 lodicules and 3 stamens (Fig. 5). Fruit is a caryopsis (grain) partially covered by glumes, round and bluntly pointed consists of embryo; endosperm and seed coat consists of pericarp and testa (Fig. 6). Coleoptiles and roots emerge from the germinating seeds.

Fig.5: Inflorescence and spikelet of *Sorghum bicolor* subsp. *bicolor* 1) Part of panicle: a. internode of rachis, b. node with branches, c. branch with several racemes; 2) Raceme: a. node, b. internode, c. sessile spikelet, d. pedicel, e. pedicelled spikelet, f. terminal pedicelled spikelets, g. awn; 3) Upper glume: a. keel, b. incurved margin; 4) Lower glume: a. keel, b. keel wing, c. minute tooth terminating keel; 5) Lower lemma: a. nerves; 6) Upper lemma: a. nerves, b. awn; 7) Palea; 8) Lodicules; 9) Flower: a. ovary, b. stigma, c. anthers; 10) Grain: a. hilum; 11) Grain: a. embryo mark, b. lateral lines (From Snowden, 1936), (Artist Gerald Atkinson, Royal Botanical Gardens, Kew.)

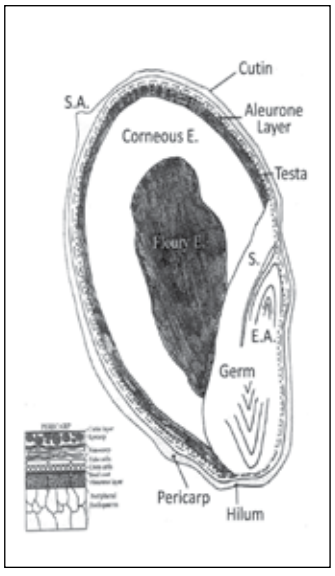


Fig.6: Structure of sorghum grain Sorghum grain showing the pericarp (cutin, epicarp, mesocarp, cross cells, tube cells, testa, pedicel, and stylar area (SA)); endosperm (aleurone layer, corneous and floury); germ (scutellum (S) and embryonic axis (EA)),

(**Source:** Rooney and Miller, 1982)

1.3 Economic Importance

Sorghum is a coarse grain, primarily used as food in semi-arid tropics and sub tropics of Asia and Africa and an important feed grain and fodder crop in the Americas and Australia. Sorghum is the principle source of energy, protein, vitamin, minerals, and trace elements for millions of the poorest people (Table 2). Sorghum grain has certain properties that make it suitable to be consumed by people suffering from chronic disorders. The nutritional value along with specific nutrients in the grain has been found to prevent and control life style diseases and disorders. Gluten-free sorghum food is recommended for gluten-intolerance and celiac patients, relatively low glycemic index and low glycemic sorghum food reduces the risk of diabetes. Sorghum has low fat content and rich source of antioxidants, polyphenols, dietary fiber, and magnesium (Ciacci *et al.*, 2007; Dayakar Rao *et al.*, 2014)

Sorghum grain/flour is used to make Roti (unleavened bread), Sankati, Annam, Pops, and Ganji (thin porridge) in rural India. Some of the value-added sorghum products available commercially in India are sorghum-rich multigrain Atta, sorghum Rawa (fine and coarse rawa for Upma, Dosa and Idli), extruded products (Vermicelli and Pasta), flaking (breakfast cereal), baked products (Biscuits and Cookies) and instant mixes (Dosa mix, Idli mix and Peda mix) (Dayakar Rao *et al.*, 2014).

Sweet sorghum is the only crop providing grain and stem that can be used as substrates for the production of sugar, alcohol, syrup, fodder, fuel, bedding, roofing, fencing, and paper (Laopaiboon et al., 2007). The juicy stalks of sweet sorghum, which is similar to sugarcane is utilizing for

Table 2. Nutritional composition of sorghum grain

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

(**Source:** Hulse *et al.*, 1980; Subramanian and Jambunathan, 1980; Makokha *et al.*, 2002)

preparation of syrup and jaggery. Sorghum grain is germinated, dried, and ground to form malt, which is used as a substratum for fermentation in beer production. A waxy sorghum identified in Mexico (a mutant variety that is nearly 100% amylopectin) may be advantageous for brewing; however, normal sorghum (approximately 75% amylopectin and 25% amylose) is more commonly used for beer production (Del Pozo-Insfran *et al.*, 2004; Figueroa *et al.*, 1995).

The stover remaining after harvesting the grain is cut and fed to cattle, sheep and goats, or may be grazed. Some farmers grind harvested stover and mix it with sorghum bran or salt to feed livestock. Brown midrib (BMR) lines of *Sorghum bicolor* were used as forage sources for livestock because of their reduced lignin content and higher digestibility of the stover (Aydin *et al.*, 1999; Oliver *et al.*, 2004). Broom sorghum (broomcorn, *S. vulgare*) is also used as a source of animal feed in some regions, although it is less digestible than *S. bicolor* (Nikkhah *et al.*, 2004). Sudangrass and its hybrids may be used as pasture, hay, green chop, or silage for livestock.

Sweet sorghums are used for the production of syrup or molasses, and are being considered as potential sources for fuel ethanol (Gibbons *et al.*, 1986). Production of ethanol from sorghum grain or sweet sorghum biomass (stalks) has gained increasing interest in recent years (Ali *et al.*, 2008; Gibbons *et al.*, 1986; Wang *et al.*, 2008; Zhao *et al.*, 2008). To produce ethanol from sorghum grain, the whole grain is ground, gelatinized, and converted to fermentable carbohydrates using enzymes. The product, distillers' grains, contains approximately 30% protein, and is commonly used as feed for livestock in either wet or dry form (Al-Suwaiegh *et al.*, 2002; Lodge *et al.*, 1997; Rooney and Serna-Saldivar, 2000).

1.4 Health Considerations of Sorghum

Sorghum is known for its good source of energy, vitamins and minerals including trace elements and also associated with various beneficial properties (Dayakar *et al.*, 2014).

1.4.1 Medicinal values of Sorghum

Celiac disease (CD) is an immune-mediated enteropathy triggered by the ingestion of gluten in genetically susceptible individuals and is one of the most common lifelong disorders worldwide. Consumption of gluten free sorghum products can be suitable for individuals suffering from celiac disease (Mustalahti *et al.*, 2002; Taylora *et al.*, 2006; Ciacci *et al.*, 2007; Pontieri *et al.*, 2013). Sorghum is rich in dietary fiber and has low glycemic index, which help in the lower plasma glucose level and control of diabetes (Lakshmi and Vimala, 1996; Abdelgadir *et al.*, 2005; Farrar *et al.*, 2008; Park *et al.*, 2012). Consumption of sorghum may have positive health impact on people suffering from cancer (Van Rensburg, 1981; Grimmer *et al.*, 1992; Gomez-Cordoves *et al.*, 2001; Yang *et al.*, 2009).

1.4.2 Natural toxicants in Sorghum

Sorghum can contain a cyanogenic glycoside that can produce Hydrogen cyanide (HCN) during times of stress or if damaged by frost or mastication. Sorghum can also accumulate toxic levels of nitrates. Cattle and rarely horses have been poisoned (Kingsbury, 1964, Gray *et al.*, 1968, Clay *et al.*, 1976).

1.4.3 Allergens in Sorghum

Sorghum pollen sensitivity has been recognized as a potential health problem in causing bronchial asthma (Pawar, 2002; Sridhara *et al.*, 2002).

1.4.4 Allelopathic properties in Sorghum

Sorghum is well recognized for its allelopathic effects on other crops and mature sorghum plants possess a number of water soluble allelochemicals which are phytotoxic to the growth of certain weeds (Putnam and DeFrank, 1983; Cheema *et al.*, 1997; Rice, 1984; Cheema and Khaliq, 2000).

2. AREA, PRODUCTION AND PRODUCTIVITY OF SORGHUM

2.1 Geographic Distribution

Sorghum is a tropical grain grown primarily in semi-arid parts of the world. In Africa, a major growing area runs across West Africa south of the Sahara, through Sudan, Ethiopia, and Somalia. It is grown in Egypt and Uganda, Kenya, Tanzania, Burundi, and Zambia. It is an important crop in India, Pakistan, Thailand in central and northern China, Australia, in the drier areas of Argentina and Brazil, Venezuela, USA, France and Italy. Globally, Sorghum is cultivated in an area of 42-43 million hectares to produce 59-60 million tonnes. In the last 18 years (1994-2011) average production of Sorghum in the world is 59-60 million tonnes. The Compounded Annual Growth Rate (CAGR) in global production of sorghum has slightly declined by -0.5% (Fig. 7). United States of America is the largest producer of sorghum in the world followed by India, Nigeria and Mexico. The compounded growth during these periods was -4.3% annually (Table 3).

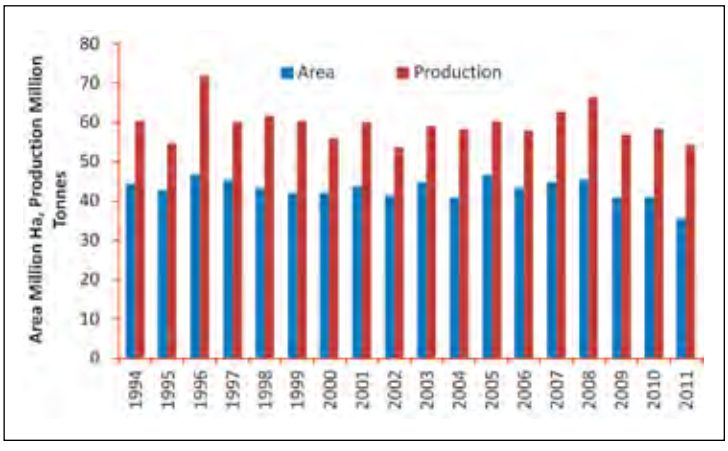


Fig.7: Global production trends of sorghum
(**Source:** FAO statistics)

Table 3: Country-wise production of sorghum in the world

S. No.	Country	Average Production (1994-11)	Share in World Production (%)	Growth (%)
1	United States of America	11.91	20	-4.3
2	India	7.81	13.1	-1.7
3	Nigeria	7.68	12.9	0.6
4	Mexico	5.94	10	1.7
5	Sudan (former)	3.47	5.8	0.2
6	China	3.13	5.3	-6.8
7	Argentina	2.77	4.7	1.5
8	Ethiopia	1.92	3.2	6.9
9	Australia	1.84	3.1	3.4
10	Burkina Faso	1.39	2.3	3.2
11	Brazil	1.16	2	12.5
12	Egypt	0.83	1.4	0.6
13	Mali	0.79	1.3	4.4
14	Chad	0.53	0.9	3.1
15	**World**	**59.42**		**-0.3**

(**Source:** FAO, various issues)

2.2 Distribution in India Including Regions of Cultivation and Existence of Naturalized Populations

Sorghum is third important cereal in India after rice and wheat. In India, sorghum is cultivated mainly in two season viz., kharif, and rabi. Kharif sorghum is characterized by coverage of hybrids producing higher yields while Rabi sorghum predominantly is characterized by improved varieties for grain, and fodder yield. In the last 20 years (1993-2012), India on an average produced around 8.0

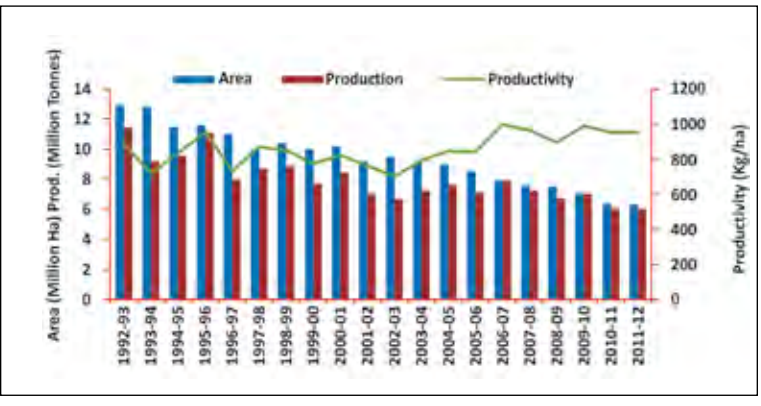


Fig.8: Average Area, production and productivity of sorghum in India (**Source:** FAO statistics)

million tonnes of sorghum from an area of 9.4 million hectare. Average productivity during the period was 900 kg/ha. There is a minor decline in Compounded Annual Growth Rate (CAGR) of area (-3.5%) and production (-2%) during the same period. The yield or productivity of Sorghum has increased substantially. Average yield during the last 10 years was 874 kg/ha and in the last five years average yield recorded was around 950 kg/ha (Fig. 8). It is important to consider that though the area under sorghum cultivation is declining from year to year, the production levels have not declined drastically owing to adoption of improved cultivars. The Compounded Annual Growth Rate (CAGR) in yield during the years 1993-2011 was 1%, and during last 10 years (2002-2011) it is 3%.

Maharashtra is the largest producer of sorghum in India. The state occupies almost 35% of the total cultivated area and 41.5% of the total production of sorghum in the country. Karnataka and Madhya Pradesh are second and third largest producers of sorghum in the country respectively. These three states together contribute around 62% in the total production. Andhra Pradesh, Rajasthan, and Tamil Nadu are the other major sorghum producing states in India (Fig. 9).

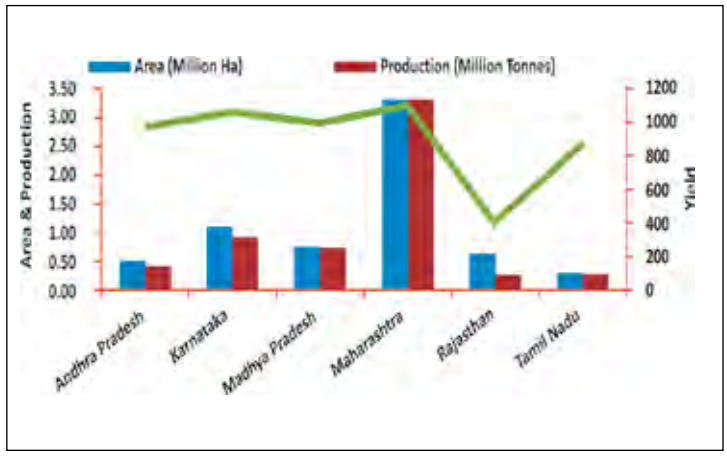


Fig.9: State-wise average area, production and yield of sorghum (1993-2011)

(**Source:** Directorate of Economics and Statistics, DAC, Ministry of Agriculture, Govt. of India)

Productivity of sorghum in Rajasthan is the lowest, mainly because it is grown under rainfed conditions and the residue moisture in the soil is lesser compared to the other sorghum producing states (Fig. 10). Total average area under sorghum in the country during 1993-2011 was 9.41 million hectare. Total average production of sorghum in the country during the year 1993-2011 was 7.98 million tonnes (Fig. 11; Dayakar Rao *et al.*, 2014).

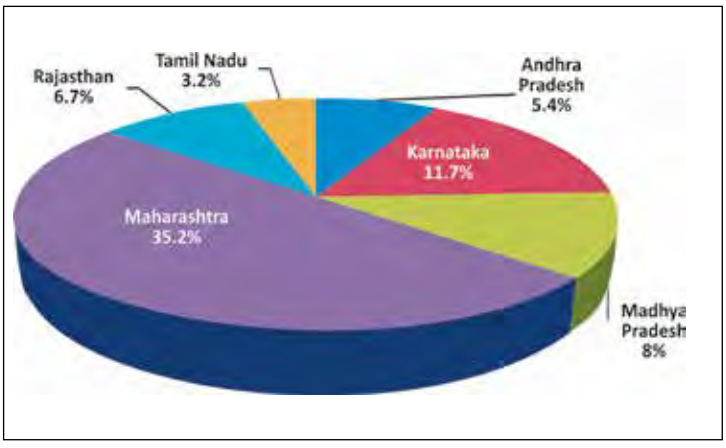


Fig.10: Major sorghum cultivating states % contribution in total average area (1993-2011)

(**Source:** Directorate of Economics and Statistics, DAC, Ministry of Agriculture, Govt. of India)

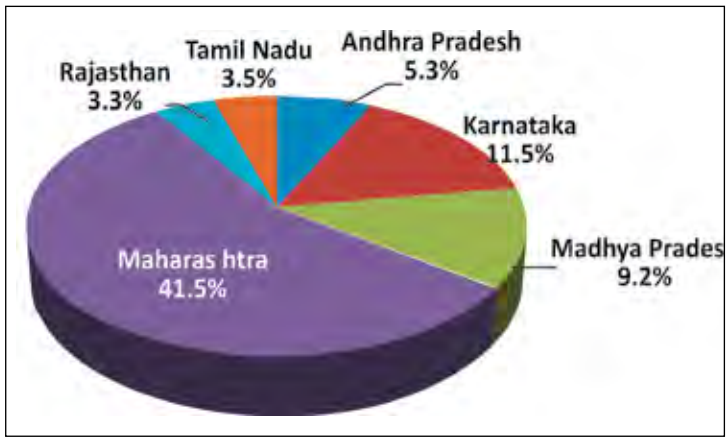


Fig.11: Major sorghum cultivating states % contribution in total average production (1993-2011)

(**Source:** Directorate of Economics and Statistics, DAC, Ministry of Agriculture, Govt. of India)

2.3 Zonalization of Varietal Testing System

Indian Council of Agricultural Research (ICAR) established All-India Coordinated Sorghum Improvement project (AICSIP) in 1969 at Indian Agricultural Research Institute (IARI), New Delhi, with 11 cooperating centers positioned in different State Agricultural Universities (SAU). The coordinating unit was shifted to IARI Regional Station, Hyderabad in 1970. More AICSIP centers were added in the subsequent five year plans. The IARI regional station at Hyderabad was reframed as the ICAR-National Research Center for Sorghum (NRCS) in 1987 then as an ICAR-Directorate of Sorghum Research (DSR), later in 2014 as an ICAR-Indian Institute of Millets Research (IIMR) and the AICSIP was integrated with this center.

At present, the AICSIP has 18 centers, spread throughout the sorghum-growing areas of the country, covering the kharif and rabi types of sorghum. Thirteen of the 18 centers conduct research on kharif sorghum (Akola-Maharashtra, Phaltan-Maharashtra, Indore-MP, Palem-AP, Coimbatore-Tamil Nadu, Surat-Gujarat, Deesa-Gujarat, Udaipur-Rajasthan, Pantnagar-Uttaranchal, Mauranipur-UP, Meerut-UP, Hisar-Haryana, and Kovilpatti-Tamil Nadu), while 3 centers (Rahuri-Maharashtra, Bijapur-Karnataka and Tandur-AP) concentrate on rabi sorghums. Two centers work on both kharif and rabi sorghums (Dharwad and Parbhani). Hisar, Pantnagar, and Deesa centers also conduct research on forage sorghum (Fig. 12).

The mandate of the centers is to develop superior hybrids and varieties combining high yield and acceptable quality of grain and fodder, wider adaptability. Resistance to major stress factors, both abiotic and biotic, to evolve appropriate crop management practices and formulate efficient sorghum-based cropping systems for sustainable sorghum production in each zone, to conduct investigations on key or potential pests and diseases of sorghum and identify and evolve elite sources of resistance to develop suitable integrated

plant protection strategies, and to promote research and extension to meet local needs within each state through SAUs and other partners. The promising breeding materials are tested in the initial variety trial for two years. The breeding lines performed well in initial trial were grouped to form advanced variety trials and tested for two more years with suitable check entries.

Fig.12: All India Coordinated Sorghum Improvement Project (AICSIP) Centers in India

3. GEOGRAPHIC ORIGIN, GENOMIC EVALUATION AND CHROMOSOME NUMBER

3.1 Center(s) of Origin and Diversity

The origin and early domestication of sorghum took place in northeastern Africa, north of the Equator and east of 10°E latitude approximately 5000 years ago (Mann et al., 1983). New evidence, however, may place the origin at 8000 years before present (BP), 3000 years earlier than previously thought and 10-15° latitude further north than had been reported earlier, since carbonized seeds of sorghum, with consistent radiocarbon dates of 8000 years BP, were excavated at an early Holocene archaeological site E-75-6, at Nabta Playa, near the Egyptian-Sudanese border (Wendorf *et al.*, 1992).

Early domestication of sorghum occurred from Ethiopian borders extending west through Sudan and up to Lake Chad (Harlan, 1975). There is great prevalence of diversity in this area as apart from the presence of the primitive race *bicolor* (Harlan and de Wet, 1972). It is likely that this race arose from the domestication of *aethiopicum verticilliflorum* complex some 3000 to 5000 years ago. The finding at Nabta Playa may cause some rethinking of dates; however, it is not clear if these 8000 year old seeds were from plants that did not shatter grains, although altered chemical composition would indicate some selection. *Bicolor* sorghum has spread across much of the old sorghum growing world including India. It is the likely progenitor of the *kaoliongs* of China (Mann *et al.*, 1983).

The race *guinea* arose from bicolor with possible interaction with the wild race *arundinaceum* in the high rainfall areas of West Africa. The *guinea* is now the dominant sorghum of West Africa but has spread also around Tanzania and Malawi. The *guinea* race arose more than 2000 years ago.

The race *caudatum* also possibly evolved from bicolor. Today, the *caudatums* are most abundant from east Nigeria to eastern Sudan and southward into Uganda. The race *durra* was selected from early *bicolor* that had moved into India some 3000 years ago. With Arab migration the durra moved into Ethiopia around 615 A.D and is today the dominant race in India, Ethiopia, the Nile Valley of Sudan, and Egypt. Race *kafir* was probably derived from *bicolor* but there is also evidence of association with the wild race *verticilliflorum*. The *kafir* is found primarily in eastern and southern Africa (Mann *et al.*, 1983). Later sorghum found its way into the Americas after 1850.

Africa has largest diversity of cultivated and wild sorghum (Doggett, 1988; deWet and Harlan, 1971; deWet, 1977). In Indian subcontinent, evidence for early cereal cultivation was discovered at an archaeological site in western parts of Rojdi (Saurashtra) dates back to about 4500 before present (Damania, 1980) and considered to be secondary center of origin of sorghum. Vavilov (1951) indicated that Ethiopia was a center of diversity; and the center of origin of sorghum. Harlan (1971) expanded on Vavilov's work and proposed that agriculture originated independently in three different areas and that, in each case, there was a center of origin and several non-centers in which activities of domestication were dispersed over a spatial span of 5000 to 10000 kilometers.

Southern Eurasia, east to India is the native of *Sorghum halepense*, a perennial plant with well developed, creeping rhizomes, and has been introduced as a weed to all warm temperate areas of the world (de Wet, 1978). *Sorghum propinquum* is another perennial with stout rhizomes and occurs primarily in Sri Lanka and southern India. It is also found between Burma eastward to the islands of southeastern Asia. *S. bicolor* has two wild subspecies associated with it, *S. bicolor* subsp. *drummondii* and *S. bicolor* subsp. *verticilliflorum*. Subspecies *drummondii* is an annual weed associated with both cultivated sorghums and their wild relatives. Subspecies *drummondii* occurs primarily in Africa and hybridizes with subspecies bicolor; all wild relatives to produce shattercane type weeds.

3.2 Genomic Evolution

Most of the cultivated sorghum varieties and land races belong to *S. bicolor* subsp. *Bicolor* of the Eu-Sorghum sub generic section of the Sorghum genus and other four, *Chaetosorghum, Heterosorghum, Parasorghum* and *Stiposorghum* contain 19, wild species native to Africa, Asia and Australia. The S. bicolor is diploid (2n = 20), *Chaetosorghum* and *Heterosorghum* contain the tetraploid (2n = 40). The ploidy varies in Parasorghum from 2n = 10 to 2n = 40 and most of species in *Stiposorghum* are diploid with 2n = 10, while *S. interjectum* has 2n = 30, 40 and *S. plumosum* has 2n = 10, 20, 30 (Garber, 1950; Lazarides *et al.*, 1991; Dillon *et al.*, 2007).

3.3 Genetic Diversity of Indian Germplasm

During 1960s Rockefeller Foundation with Indian Agricultural Research Program collected a total of 16,138 accessions from different countries and International Sorghum (IS) numbers were assigned to them (House, 1985; Murty *et al.*,

1967). At present, ICRISAT is a major repository for the world sorghum germplasm collection with a total of 36,774 accessions from 90 countries. The existing collections of sorghum germplasm conserved at ICRISAT have been estimated to represent about 80% of the variability present in the crop (Eberhart *et al.*, 1997). About 90% of these collections have come from developing countries in the semi-arid tropics. About 60% of these collections have come from six countries: India, Ethiopia, Sudan, Cameroon, Swaziland, and Yemen.

The largest collection is from India. In addition to this, the germplasm maintained at ICRISAT, India, are classified into five races: bicolor, guinea, caudatum, kafir and durra and their derivative (Gopal Reddy *et al.*,2002). The collection is predominantly represented by three basic races: *durra* (21.8%), *caudatum* (20.9%), and *guinea* (13.4%). Among the intermediate races, *durra-caudatum* (12.1%), *guinea-caudatum* (9.5%) and durra-bicolor (6.6%) are common (Reddy *et al.*, 2008). At ICAR-IIMR, India a total of 20,812 accessions conserved at medium-term storage along with 1456 accessions as duplicates. The maximum accessions are a repatriation material (11,113 acc.) followed by other IS lines (3442 acc.). Local germplasm (3560 acc.) and exotic collections (494 acc.) are other important materials. 9984 accessions of sorghum genetic resources are held at AICSIP centers. 2373 accessions of specific sorghum germplasm are held at 7 AICSIP centers.

Genetic diversity among sorghum accessions from ex *situ* germplasm collections were assessed using different generations of molecular markers. RFLPs have been employed effectively to study genetic diversity in sorghum and molecular marker analysis (Aldrich and Doebly, 1992; Deu *et al.*, 1994; Cui *et al.*, 1995; Deu et al., 2006). Subsequently, other markers systems like RAPD (Menkir et al., 1997; Ayana *et al.*, 2000a; Ayana *et al.*, 2000b; Jeya Prakash *et al.*, 2006), AFLP (Menz *et al.*, 2004; Arya *et al.*, 2008), SSR (Brown *et al.*, 1996; Taramino *et al.*, 1997; Ghebru *et al.*, 2002; Casa *et al.*, 2005; Deu *et al.*, 2008; Sagnard *et al.*, 2011; Billot *et al.*, 2013; Ramu *et al.*, 2013; Wu and Huang, 2006), DArT (Mace *et al.*, 2008; Bouchet *et al.*, 2012) and SNP (Nelson *et al.*, 2011; Zheng *et al.*, 2011; Billot *et al.*, 2012, 2013).

In India two distinct adaptive types of sorghum are under cultivation, viz., kharif (rainy season) and rabi (post-rainy season). The kharif season cultivars are predominantly caudatum, kafir and bicolor races, while rabi cultivars are mainly durra types. Molecular markers were employed to distinguished the parental lines of hybrids, and races (Ganapathy *et al.*, 2012; Rakshit *et al.*, 2012), to identify the diverse parents for developing mapping populations (Madhusudhana *et al.*, 2012), and to study the genome wide association traits in sorghum (Sukumaran *et al.*, 2012).

4. REPRODUCTIVE BIOLOGY OF SORGHUM

4.1 Reproduction of Sorghum

Vanderlip and Reeves (1972) described the temperate sorghum growth stages on a scale of 0-9. However, the duration of these stages varied according to the climatic conditions, latitude, date of planting, and temperature. Eastin (1972) reported three simplified sorghum growth stages, i.e., i) planting to panicle initiation (GS1; corresponding to Vanderlip 1-3 stages), ii) panicle initiation to flowering (GS2; corresponding to Vanderlip 4-6 stages), and iii) flowering to physiological maturity (GS3; corresponding to Vanderlip 7-9 stages). Seetharama (1977) described the variation in GS1, GS2, and GS3 in the range of 31-48, 29-64, and 31-56 days, respectively among sorghum genotypes representing important germplasm. It is essential to understand as to how the sorghum develops and differentiates into yield components to manage the crop. The variation in growth stages of temperate sorghum described by Vanderlip and Reeves (1972) is inadequate to characterize the Indian tropical sorghums, where the growing conditions and seasons are different from those of temperate countries and mostly photoperiod-insensitive materials are used. Rao et al. (2004) described the various growth stages using kharif sorghum commercial hybrid, CSH 16 on a 0-9 scale and each number in the scale corresponds to a specific growth stage.

4.1.1 Sorghum growth stages

4.1.1.1 Stage 0: Emergence

Emergence occurs when the coleoptile is visible at the soil surface, which normally takes 4 days after sowing (Fig. 13). However, appearance of coleoptile may vary between 4 and 7 days from planting depending upon the, soil moisture, depth in planting, temperature, compaction of soil, and seed vigor.

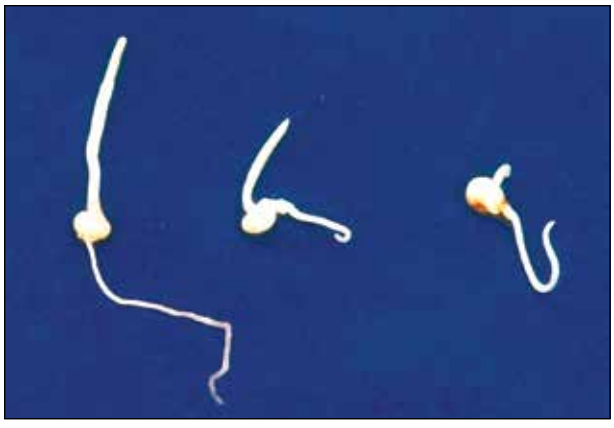


Fig.13: Newly emerged seedlings

4.1.1.2 Stage 1: 3-leaf stage

At stage 1, seedling has three fully expanded leaves (the collar of 3 leaves is clearly visible). This takes about 6 days after emergence (Fig. 14). However, the seedling growth during this stage is mostly depends upon the temperature, and may attain 15-20 cm height.

Fig.14: Sorghum plant at 3- leaf stage

4.1.1.3 Stage 2: 5- leaf stage

This stage is characterized by the appearance of visible ligule in the fifth leaf, which is long with pointed tip unlike the first leaf with round tip (Fig. 15). It takes about 16 days from emergence, and grows 40-50 cm tall. The seedlings enter grand period of growth' from this stage. Root system develops rapidly and dry matter accumulates at a constant rate, if the growing conditions are favorable.

Fig.15: Sorghum plant at 5- leaf stage

4.1.1.4 Stage 3: Panicle initiation stage

At 32 days after emergence, the growing point transforms from vegetative (leaf producing) to reproductive (panicle producing) phase (Fig. 16). Plant grows to a height of 85-100 cm. Panicle initiation can be identified by splitting the stalk with a sharp knife and observed under compound microscope (rounded apex >0.5 mm). During this stage, plants have 8-9 leaves. The basal 2-3 leaves may become senesced. Culm growth increases rapidly following this stage. All commercial tropical cultivars generally commence stem elongation prior to panicle initiation, while their temperate counterparts with 2-dwarf genes, and generally initiate the panicle prior to stem elongation.

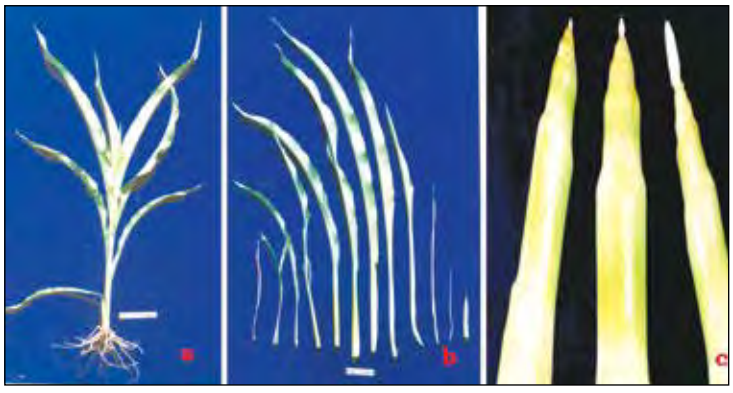


Fig.16: Sorghum panicle initiation

a) Pictures showing sorghum plant at panicle initiation stage, **b)** Sorghum plant parts separated,
c) Initiation of panicle primordial

4.1.1.5 Stage 4: Flag leaf (final leaf) visible in whorl

At this point all except the final 3 to 4 leaves are fully expanded representing approximately 80% of the total leaf area potential. The lower 3 to 5 leaves of the plant have been lost due to senescence and any reference to leaf number from this stage on should be from the top, counting the flag leaf as leaf number one. It takes about 50 days from emergence, 18 days from stage 3, and can be identified by observing the appearance of tip of flag leaf in the whorl (Fig. 17). Plants show rapid leaf and culm elongation.

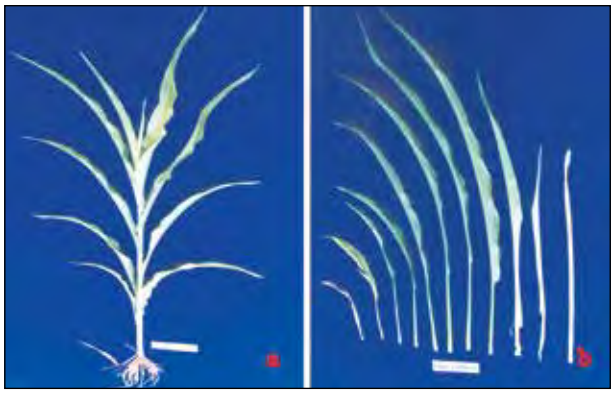


Fig.17: Sorghum flag leaf stage

a) Sorghum plant at flag leaf visible stage, b) Sorghum plant parts separated

4.1.1.6 Stage 5: Boot stage

Boot leaf can be identified as a swollen flag leaf sheath enclosing the panicle which gives the appearance of boot shape (Fig. 18). It takes 60 and 10 days from emergence and stage 4, respectively. Flag leaf is the last leaf to emerge from the whorl. Panicle development is completed, and plant reaches with maximum leaf area. Plant grows to a height of 125-130 cm tall, and potential panicle size is determined. The last internode, peduncle begins elongating and results in panicle exertion from flag leaf sheath.

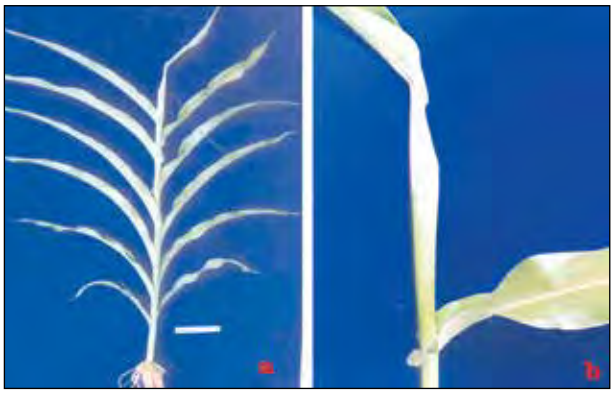


Fig.18: Sorghum boot stage

a) Sorghum plant at boot stage, b) Detailed view of boot portion of the plant

4.1.1.7 Stage 6: 50% flowering

This stage can be identified when half the plants in the field are in anthesis (Fig. 19). It takes about 68 days from emergence and 8 days from stage 5. Plant grows to a height of 150-160 cm. Flowering typically starts in 5-7 days after panicle exertion, when the appearance of yellow anthers from the top. 50% of the anthers on 50% of the plants in the field indicate 50% flowering. Flowering duration (from starting to end) usually takes 4-9 days depending upon the cultivar. By this stage, plants accumulate about one half of the total plant dry weight.

Fig.19: Sorghum at 50% flowering stage

a) Sorghum plant at 50 % flowering stage, b) Detailed view of panicle showing progression of anthesis from top to bottom

4.1.1.8 Stage 7: Soft dough stage

Following flowering, grain development progress from milk through soft dough stage, at this stage, the developing grain is squeezed between fingers; milk will ooze out (Fig. 20). It usually takes about 80 days from emergence, and 12 days from 50% flowering. This stage signals the end of culm elongation. Approximately 50% of grain weight is accumulated by soft dough stage. Usually 8-10 functional leaves are present and this may vary with the cultivar with stay green ones retain more. Plant reaches about 170 cm tall.

Fig.20: Soft dough stage a) Sorghum plant at soft dough stage, b) Detailed view of upper half

4.1.1.9 Stage 8: Hard dough Stage

During this stage, the grain is hard and cannot be flattened by pressing in between the fingers. It takes about 96 days from emergence and about 16 days from stage 7 (Fig. 21). The culm declines to its lowest weight, with few leaves shed due to senescence. Plants at this stage are also susceptible to lodging due to moisture stress and charcoal rot. Lodging also occurs by defoliation due to insect pests and diseases during flowering through hard dough stage.

Fig.21: Hard dough stage a) Sorghum plant at hard dough stage, b) Detailed view of upper half of the plant

4.1.1.10 Stage 9: Physiological maturity

Maximum total dry weight of the plant has occurred. This stage is determined by the dark black spot appears at the basal portion of seed (Fig. 22). Physiological maturity usually occurs in 106 days from emergence and 10 days after hard dough stage. Seed moisture content at this stage varies between 25% and 35%, and seeds gain maximum dry weight. Flowering to physiological maturity period varies with the cultivar and environmental conditions, and takes about 38-45 days among the commercial cultivars (Fig. 23).

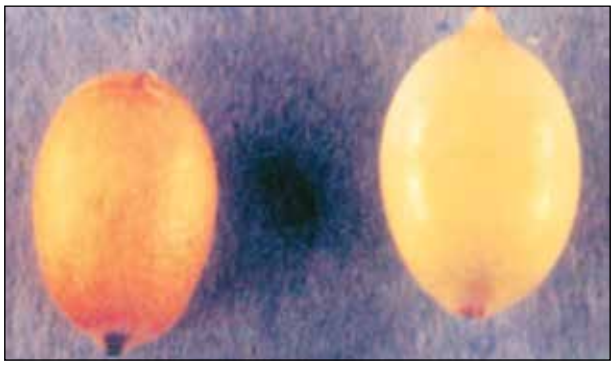


Fig.22: Picture showing the physiologically mature seed with dark black spot

Fig.23: Physiological maturity a) Sorghum plant at physiological maturity, b) Detailed view of upper half

4.2 Methods of Pollination, known Pollinators and Pollen Viability

Sorghum bicolor is propagated through seeds produced by self-pollination, but outcrossing rates are in the range of less than 10% to 73% (Ellstrand and Foster, 1983; D'je *et al.*, 2004; Barnaud *et al.*, 2008) and to nearly 100% in individual sudan grass plants (Pedersen *et al.*, 1998). Wind is an important vector for significant rates of outcrossing (Stephens and Quinby, 1934) and insects (honeybees, wild bees, beetles) may also contribute to cross pollination (Stephens and Quinby, 1934; Immelman and Eardley, 2000; Schmidt and Bothma, 2005).

Sorghum pollen is generally highly functional for about 30 minutes after the anthers dehisce, but its longevity is limited to two to four hours (Schertz and Dalton, 1980; Lansac *et al.*, 1994). Pollen kept under refrigeration is capable of fertilization for three to four days (Sanchez and Smeltzer, 1965). Pollen viability and ability to germinate are influenced by temperature, humidity, and cloud cover (Artschwager and McGuire, 1949; Brooking, 1979, Tuinstra and Wedel, 2000). Stigmas are receptive for a day or two after blooming, but may remain receptive up to a week or more (Ayyangar and Rao, 1931; Stephens and Quinby, 1934; Maunder and Sharp, 1963). The average number of sessile spikelets in a single inflorescence of sorghum is estimated by as 2000 to 4000 (Ayyangar and Rao, 1931) and each spikelet has 3 anthers with an average of 5000 pollen grains in each (Stephens and Quinby, 1934). The amount of pollen shed by anthers is a highly variable trait, depending on the genotype (Murty *et al.*, 1994).

4.3 Seed Development and Dispersal

The pollen grains germinate immediately after contact with receptive stigma. However, Artschwage and McGuire (1949) reported that sorghum pollen requires light and germinates only after daybreak. The pollen tubes grow through the stigmatic papiuae down the ovary, through style. Fertilization between egg-cell and sperm takes place within two hours and develops into an embryo (2n). Second fertilization occurs between polar nuclei and sperm and develops into an endosperm (3n). The seed development reaches physiological maturity with 30 to 40 days after fertilization.

The ripe seed (grain) of sorghum is usually partially enclosed by glumes, which are removed during threshing and/or harvesting. The shape of the seed is oval to round and the color may be red, white, yellow, brown, or shades thereof. If only the pericarp is colored, the seed is usually yellow or red. Pigment in both the pericarp and testa are in a dark-brown or red-brown color. The sorghum grain consists of the testa, embryo, and endosperm. The seed coat consists of the pericarp and testa. Pericarp is the outermost layer of the seed and consists of the epicarp, hypodermis, mesocarp, and endocarp. The testa is situated directly below the endocarp and encloses the endosperm. The seeds of sorghum species can be spread via wind, water, animals, or humans (clothing, harvest machinery, vehicles) and can travel to long distance when carried by birds or livestock (Holm *et al.*, 1977; Warwick and Black, 1983).

4.4 Potential for Vegetative Propagation

Domesticated sorghum is not capable of vegetative reproduction, but *Sorghum halepense* or Johnsongrass are perennial wild relatives of sorghum as well as other two sexually compatible perennials *S. propinquum* and *S. x almum* (Columbus grass) were capable of spreading vegetatively and persisting because of its well-developed rhizomes (McWharter *et al.*, 1971; Holm *et al.*, 1977; Warwick *et al.*, 1986; Arriola and Ellstrand, 2002).

5. HYBRIDIZATION AND INTROGRESSION

5.1 Naturally Occurring Interspecific Crosses

Sorghum is highly self-pollinated but capable of varied frequencies of outcrossing. As a result, spontaneous hybridization between cultivated and wild weedy sorghum results in intermediary, often weedy sorghum forms (Ejeta and Grenier, 2005). Depending on the level of cross-compatibility with the wild relatives; sorghum can be divided into primary and secondary gene pools (Table 4).

Primary Gene Pool (GP-1): The primary gene pool includes *Sorghum bicolor* crop-wild-weed complex and the diploid perennial wild relative *S. propinquum* (Kunth) Hitchc. The crop-wild-weedy complex consists of domesticated sorghum (*Sorghum bicolor* subsp. *bicolor*) and its wild ancestor *S. bicolor* subsp. verticilliflorum and the annual weedy sorghums *S. bicolor* subsp. *drummondii* and *shattercane*. All these taxa are fully interfertile and can spontaneously outcross with each other in areas where their distributions overlap, leading to frequent introgression among them (Doggett and Majisu, 1968; Baker, 1972; Doggett and Prasada Rao, 1995; Anderson and Carmen, 2010). The S. African sorghum race Kafir might have arisen from introgression between domesticated and wild sorghum (Mann *et al.*, 1983) and all other African sorghum races are diversified by introgression with wild sorghum (Doggett and Prasada Rao, 1995).

Secondary Gene Pool (GS-2): The secondary gene pool of domesticated sorghum includes Columbus grass (*Sorghum x almum*) and one of the world's worst weeds, Johnson grass (*S. halepense*). Despite differences in ploidy level, diploid domesticated sorghum readily outcrosses with tetraploid wild relatives under controlled and natural conditions (Arriola and Ellstrand, 1996; Morrell *et al.*, 2005). *Sorghum halepense* (L.) Pers. found throughout Africa, Southern Europe, and Asia (Price *et al.*, 2005; de Wet, 1978) and become naturalized and is considered a noxious invasive weed. *S. halepense* possesses one sub genome that is similar to *S. bicolor* genome. The common wild sorghum (*S. bicolor* ssp. arundinaceum (Desv.) Stapf.) is believed to be the progenitor of modern *S. bicolor* (Hadley, 1953; de Wet, 1978; Celarier, 1958). *S. halepense* is theorized to have originated from hybridization between S. propinquum and *S. bicolor* ssp. arundinaceum followed by chromosome doubling (de Wet, 1978). *S. halepense* has approximately double the DNA content of *S. bicolor* and *S. propinquum*, with all three species having similar haploid chromosome complement sizes (Price *et al.*, 2005). The difference in DNA content between these species is largely due to levels of ploidy, with *S. halepense* being tetraploid (4x) and both *S. bicolor* and *S. propinquum* being diploid (2x). *S. x almum Parodi* (2n = 2x = 40), commonly referred to as Columbus grass, has in fact been theorized to be a naturally occurring hybrid between S. bicolor and *S. halepense* (Parodi, 1943). This species hybrid was discovered in Argentina and generally has been difficult to morphologically separate it from *S. halepense* (Parodi, 1943; Endrizzi, 1957). Sorghum halepense was reported to be a weedy wild species in the fields of soybean, pigeon pea and sugarcane in India and so far no reports of natural hybridization with cultivated sorghum (Patel *et al.*, 1993; Sharma and Sachan, 1994; Mehra *et al.*, 1994; Chandel *et al.*, 1995; Elangovan *et al.*, 2012).

5.2 Experimental Interspecific Crosses

The production of viable interspecific hybrids within the genus *Sorghum* has been rare with only limited reports in the literature. Dweikat (2005) reported interspecific hybridization between of these *S. bicolor* and a weedy wild relative Johnsongrass (*Sorghum halepense* (L.) Pers.). The hybridity confirmed by phenotypic and genotypic analyses and the F1 progeny revealed a high level of male and female fertility and subsequent self-pollination of the F_1 hybrids resulted in seed set more than 90%. Price *et al.* (2005) produced single interspecific hybrid between cytoplasmic male sterile (CMS) of S. bicolor (2n = 20) and the Australian species *S. macrospermum* Garber (2n = 40).

The tertiary gene pool of sorghum contains all the remaining species within the genus carries important genes for insects and pathogens. The discovery and use of *Iap* gene locus (Inhibition of alien pollen tubes) controls the incompatibilities between pistils of *S. bicolor* and pollen of alien species (Laurie and Bennett, 1989). Price *et al.* (2006) reported interspecific hybrids crossed between *S. bicolor* accession (Nr481) and three tertiary gene pool species: *S. macrospemum, S. nitidum* (vahl) Pers., and *S. angustum* S.T. Blake and the interspecific hybrids were verified morphologically and cytologically, but only hybrids with *S. macrospermum* survived to maturity. Kuhlman *et al.* (2008) produced interspecific hybrids by utilizing germplasm homozygous for the iap allele between S. bicolor (2n = 2x = 20; AAB1B1) and *S. macrospermum* (2n = 8x = 40; WWXXYYZZ). These hybrids were intermediate to the parents in chromosome number (2n = 30) and overall morphology.

Sorghum is considered one of the closest relatives of Sugarcane and some intergeneric crosses of sorghum x sugarcane have been reported with human intervention and a highly unlikely to occur theses crosses under natural conditions (Venkataraman and Thomas, 1932; Bourne, 1935; Janakiammal and Singh, 1936; Moriya, 1940; De Wet *et al.*, 1976; Nair, 1999; Nair *et al.*, 2006; Anderson and Carmen, 2010).

Table 4. Domesticated sorghum (*Sorghum bicolor* (L.) Moench) and its wild relatives

Species	Common name	Ploidy level	Origin and distribution	Life form and weediness
Primary gene pool (GP-1)				
S. bicolor (L.) Moench Subsp. bicolor	Grain sorghum, domesticated sorghum	Diploid (2n=2x=20)	Cultivated throughout tropic, sub tropic and warm temperate regions	Annual, cultivated grain sorghum
S. bicolor subsp. *verticilliflorum* (Steud.) deWet ex Wiersema and J. Dahlab.	Common wild sorghum	Diploid (2n=2x=20)	Native to tropical Africa, Madagascar and naturalized in India, Australia	Ancestor, wild annual
S. bicolor subsp. drummondii (Steud.) De Wet ex Davidse.	Chicken corn, Sudan grass	Diploid (2n=2x=20)	Native to Africa, but may be present wherever grain sorghum is cultivated	Noxious annual crop weed, arising from hybridization of grain sorghum (Sub sp. *bicolor*) and its wild relative (Subsp. *verticilliflorum*)
S. propinquum (Kunth.) Hitch.		Diploid (2n=2x=20)	SE Asia (Sri Lanka, S. India, Myanmar, Thailand, Malaysia and Philippines)	Wild perennial; weedy
Secondary gene pool (GS-2)				
S. x almum Parodi	Columbus grass	Allotetraploid (2n=4x=40)	Natural hybrid; arose in S America (Argentina, Paraguay and Uruguay)	Wild perennial; noxious weed in USA
S. halepense (L.) Pers.	Johnson grass, weedy sorghum	Allotetraploid (2n=4x=40)	Native to W. Asia and N. Africa; widely naturalized in warm temperature regions elsewhere, including N. America	Wild perennial; classified as a noxious weed in USA and Canada)

(**Sources:** Harlon and de Wet, 1972; de Wet, 1978; Dahlberg, 2000; Wisersema and Dahlberg, 2007)

6. KNOWN INTERACTIONS WITH OTHER ORGANISMS IN MANAGED AND UNMANAGED ECOSYSTEMS

6.1 Important Insect Pests, Nature of Damage and their Control in Managed Ecosystems

Approximately 150 insect species are reported to infest sorghum in different parts of the world. However the species of economic importance are much fewer (Sharma, 1993). An estimated grain yield losses in sorghum attributed to infestation by the main species of shoot fly, stem borer, midge and head bugs, are placed at nearly 32% in India, 9% in the USA, and over 20% in Africa (ICRISAT, 1992). The source of information and photographs on major insect pests of sorghum in India are collected from Mr. H Gawali, ICAR-Indian Institute of Millets Research (IIMR), India, Teetes *et al.* (1983), Gour *et al.* (2000), and www.agritech.tnau.ac.in.

6.1.1 Shoot fly

Atherigona soccata (Rondani) (Muscidae: Diptera)

Shoot fly is a small, grey colored, fly which deposits small, white cigar shaped eggs, singly on the under surface of the seedling leaves (Fig. 24a-b). The shoot fly population exhibits considerable

variation and normally very low in April to June, tends to increase in July and reaches the peak in August. From September onwards the population gradually declines and remains at a moderate level till March. The damage occurs from 1 week to about 1 month after emergence. The shoot fly larva feeds on the growing tip causing wilting of leaf and later drying of central leaf giving the typical deadheart symptom (Fig. 24c). The deadheart can be easily pulled out and, at the base, emits a bad smell. The promising control measures to avoid shoot fly are the adjustment of the sowing dates, high seeding, and the application of Phorate or Carbofuran granules.

Fig.24: Symptoms of shoot fly infestation
a) Adult shoot fly, b) Oviposition of shoot fly
c) Deadheart symptom

6.1.2 Spotted stem borer

Chilo partellus (Swinhoe) (Pyralidae: Lepidoptera)

The pest is very important and common in Indian subcontinent. Several species attack sorghum but *C. partellus* is by far the most important. It infests the crop from 2nd week to till maturity. Initially, the larvae feed on the upper surface of whorl leaves leaving the lower surface intact as transparent windows (Fig. 25a). As the severity of the feeding increases, blend of punctures and scratches of epidermal feeding appears prominently. Sometimes, `deadheart' symptoms also develop in younger plants due to early attack (Fig. 25b). Subsequently, the larvae bore into the stem resulting in extensive stem tunneling (Fig. 25c). After head emergence the stalk just below or on the panicle is often bored, resulting in breaking of the panicles or complete or partial chaffy seeds (Fig. 25d). There is often extensive tunneling of the stem. The borer attacks all parts of the sorghum plant except roots. Several parasites and predators are known to suppress pest density. Plowing up and destroying the stubble after harvest is strongly recommended. Early planting with a high seed rate and removal of affected plants is advantageous. Whorl application of Endosulfan or Carbofuran granules is effective.

Fig.25: Symptoms of stem borer infestation
a) Leaf feeding, b) Deadheart symptoms
c) Stem tunneling, d) Peduncle tunneling

6.1.3 Midge

Contarina sorghicola (Coquillett)
(Cecidomyiidae: Diptera)

The sorghum midge is a destructive pest to grain sorghum in India. The adult is tiny, fragile orange color fly which can be seen hovering on panicle top in early hours (Fig. 26a). Damage to sorghum is caused by larvae feeding on the ovary, preventing normal grain development and resulting in a blasted panicle (Fig. 26b). To determine the presence of

Fig.26: Midge infestation a) Egg laying by the female in glumes, b) Earhead with chaffy grains

the midge the spikelet is pressed red liquid comes out is an indication of midge infestation. A minute exit hole is also seen on the ventral side of spikelet to recognize the midge damage. Burning of panicles after threshing destroys diapausing maggots. Early and uniform planting of sorghum over large areas is the most widely accepted method of reducing midge damage. Dusting or spraying with endosulfan. Malathion or Carbaryl reduces infestation.

6.1.4 Earhead bug

Calocoris angustatus (Lethiery) (Miridae: Hemiptera)

This is a very serious pest of sorghum in certain parts of India. It inserts long cigar shaped eggs generally under the glumes or between the anthers of sorghum florets. Both nymphs and adults infest the panicles as soon as they emerge from the boot leaf and suck sap from the developing grain (Fig. 27a). Consequently grain attached in an early stage of development is shriveled, reducing crop yield (Fig. 27b). Older grain shows distinct feeding punctures that reduce grain quality. Early planting reduces the chances of flowering period coinciding with the peak activity of head bugs so as to minimize the bug damage and dusting with Carbaryl at the time of flowering is effective.

Fig. 27: Earhead bug infestation a) Adult Earhead bug, b) Earhead affected panicle

6.1.5 Shoot bug

Peregrinus maidis
(Ashmead) (Delphacidae: Homoptera)

Being a sporadic pest, under favorable conditions, it produces several generations and can cause heavy damage to sorghum. Both the adult types (Brachypterous and Macropterous) and nymphs suck the plant sap causing reduced plant vigor and yellowing (Fig 28a). In severe cases, the younger leaves start drying and gradually extend to older leaves. Sometimes, complete plant death occurs (Fig. 28b). Heavy infestation at vegetative stage may twist the top leaves and prevent either the formation or emergence of panicles. Dusting with Methyl parathion or spraying Dimethoate gives effective control of the pest.

Fig. 28: Shoot bug infestation a) Colony of shoot bug eggs and nymphs; b) Shoot bug affected plant

6.1.6 Corn leaf aphid

Rhopalosiphum maidis (Fitch)
(Aphididae: Homoptera)

The corn leaf aphid often becomes extremely abundant and is found in all sorghum-growing areas. The aphid is most commonly found deep in the whorl of the middle leaf (Fig. 29a). Both the adults and nymphs suck the sap and heavily infested leaves show yellowish blotches (Fig. 29b) and necrosis may occur on leaf edges (Fig. 29c). They produce abundant honeydew which predisposes the plant to sooty mold and other sporadic fungal pathogens. The honeydew excretion hinders harvesting process and result in poor quality grain. Severe damage was noticed under moisture stress conditions resulting in drying of leaves as well as plant death. Dimethoate, Phosphamidon or Methyl demeton is recommended if infestation is severe.

Fig.29: Corn leaf aphid infestation a) Corn leaf aphid infestation, b) Yellowish molting of leaves, c) Marginal leaf necrosis

6.1.7 Sugarcane aphid

*Melanaphis sacchari (*Zehntner)
(Aphididae: Homoptera)

This aphid prefers to eat older leaves and also infests younger leaves (Fig. 30a) and panicles at the flowering stage (Fig. 30b). Both adults and nymphs suck sap, causing stunted plant growth. The damage is more severe when the crop is under moisture stress, resulting in the drying of leaves and plant death. A large number of feed on this insect and chemical controls are usually not required. But Metasystox or Malathion is recommended if infestation is severe.

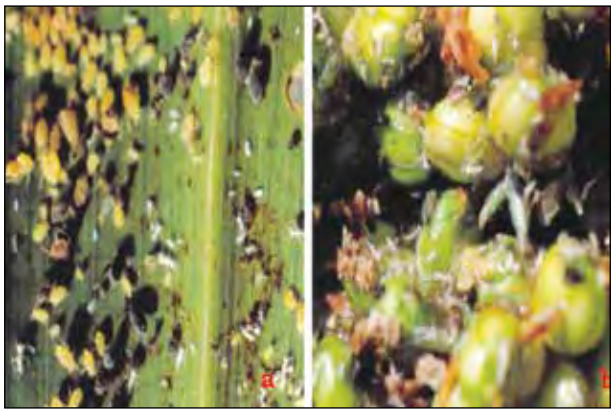


Fig.30: Sugarcane aphid infestation a) Sugarcane aphid infected older leaves, b) Sugarcane aphid infected panicles at flowering stage

6.1.8 Mites

Oligonychus indicus (Banks)
(Tetranychidae: Acarina)

Mites often cause damage to sorghum in prolonged drought conditions. Although found early in the growing season rapid population increases occurs only after the panicle emergence. They suck the plant sap first on the under surface of the functional leaves and the infested areas initially are pale yellow, but later turn to reddish (in purple pigmented cultivars) or brownish tan (in tan pigmented plants) on the upper leaf surface (Fig. 31a). This extends to the entire leaf area which spreads upwards through the plant affecting plant growth and seed development. The underside of the heavily infested leaves have dense deposits of webbing and in severe infestations they may invade

and web even the sorghum panicle (Fig. 31b). Dusting Sulfur or spraying Dicofol or ethion gives effective control.

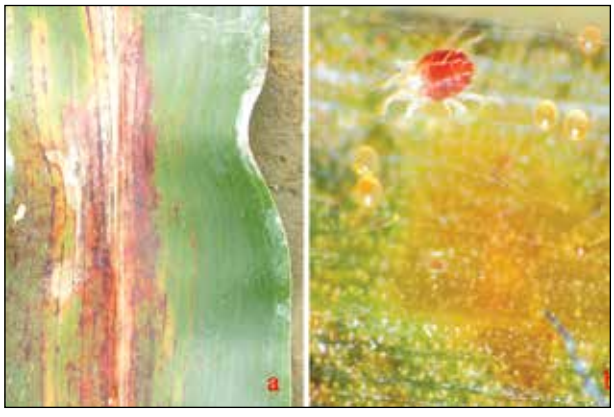


Fig.31: Mites infestation a) Mites infested leaf surface, b) Infested leaves with deposits of webbing

6.2 Important Diseases, Casual Agents and their Control in Managed Ecosystems

Diseases are major constraints to sorghum production especially in kharif season due to late rains and in rabi season may be due to moisture stress and high temperatures at grain filling stage. The source of information and photographs on major diseases of sorghum in India are collected from Mr. H Gawali, ICAR-Directorate of Sorghum Research (DSR), India (Williams *et al.*, 1978; Gour *et al.*, 2000).

6.2.1 Grain Molds

A complex of several fungal species

Grain molds are severe during the years of prolonged rainfall at the time of flowering and grain filling stages (Fig. 32). The most commonly isolated fungal species are Fusarium (*F. semitectum* and *F. moniliforme*) and grain infected with these fungi develop a fluffy white or pinkish coloration. *Curvularia lunata* is also frequently encountered

Fig.32: Grain mold infected panicle

and this fungus colors the grains black. It results in discoloration of grain, but severity of infection reduces grain weight and size leading to considerable loss of yields even up to 100%; reduces germination and acceptability of the harvested grain, nutritive value and market price. Moldy grains contain toxic mycotoxins are unfit for human consumption and cattle feed. Avoiding cultivars that mature when there is likelihood of rains is a precaution that can be used to avoid grain molds. Harvesting of genotypes at physiological maturity and drying also reduces mold incidence.

6.2.2 Downy Mildew

Sclerospora sorghi (Kulk) Weston and Uppal

Downy mildew is common in all sorghum growing areas. The symptoms vary with the stage at which plants are infected. The most conspicuous symptom is appearance of vivid green and white stripes on the leaves and providing growth on ventral side of the leaf. At advanced stage, it results into shredding of leaves and stunting of plant growth (Fig. 33a, b, c). Infested plants usually fail to head. Even if heads are exerted, they are small, compact or club-shaped

and have little or no seed. Destruction of infected plant debris, seed treatment with Metalaxyl or Mancozeb can control this disease.

Fig.33: Downy mildew infestation a) Whitish downy growth on lower leaf surface; b) Bleached stripes on leaves; c) Complete bleaching of entire leaf surface

6.2.3 Leaf blight

Trichometasphaeria turcica

Fig.34: Leaf blight infested leaves Lesions with straw colored centers and dark margins

Wide spread in all sorghum growing areas and causes losses in both grain yield and fodder quality. The leaf blight pathogen is known to cause seed rot and seedling blight of sorghum, particularly when the crop is planted in cold wet soil. On older plants the typical symptoms are long elliptical necrotic lesions, straw colored in the centers with dark margins (Fig. 34). Under humid conditions a faint grey bloom consisting of conidiophores and conidia can be observed on the lesions. The lesions can be several centimeters long by 1 to 2cm wide. Many lesions may develop and coalesce on the leaves, destroying large areas of leaf tissue, giving the crop a distinctly burnt or blasted appearance. Destruction of plant debris, treating the seeds with Thiram or Captan can control this disease.

6.2.4 Rust

Puccinia purpurea Cooke

The intensity of rust infection is generally severe after flag leaf stage. Symptoms of the disease occur as small reddish brown flecks on the lower surface of the leaf (Fig. 35a). In severe infections pustules may appear on upper surface also. The pustules are elliptical and lie between and parallel with leaf veins (Fig. 35b). Pustules are surrounded by a reddish or yellow halo. Severe infestation leads to leaf drying. Pustules also appear on leaf sheath and peduncles (Fig. 35c). Destruction of crop debris and spraying with Mancozeb are effective.

Fig.35: Rust infection a) Rust pustules on leaf, b) Severe symptoms of rust on leaf, c) Rust pustules on peduncle

6.2.5 Anthracnose and Red rot

Colletotrichum graminicola (Cesati) Wilson

This is wide spread and prevalent in all sorghum

growing areas. The fungus *Colletotrichum graminicola* causes both a leaf spot disease (anthracnose) and a stalk rot (red rot) in sorghum. The anthracnose phase is characterized by small elliptical to circular spots, up to 5mm in diameter, which develop small circular straw colored centers and wide purple, red or tan margins (depending on host cultivar). Few or numerous small black spots are seen on the surface of the centers of the lesions, which are the fruiting bodies (acervuli) of the causal fungus. Midrib infection often occurs and is seen as elongate-elliptical red or purple lesions on which the black acervuli can be clearly seen (Fig. 36a). The red rot phase may occur in stalks and/or in the inflorescences. Infected stems when split open show discoloration (depending on cultivar) which may be continuous over a large area, or more generally discontinuous, giving the stem a marbled appearance (Fig. 36b). Nodal tissue is rarely discolored. Stalk rot is usually preceded by leaf anthracnose, although in some instances little foliar disease is evident. Elimination of the collateral hosts, ploughing under of infected crop debris, crop rotation, seed treatment with Capton or Thiram and spraying of Carbendazim or Mancozeb are effective.

Fig.36: Anthracnose and Red rot infection a) Midrib infected with anthracnose seen as elongate, elliptical red or purple lesions, b) Red rot infected split open stem showing

6.2.6 Ergot

Sphacelia sorghi, Claviceps sorghi

It is commonly known as sugary disease and its first symptom is the secretion of a creamy sticky liquid (honey dew) from the infected florets (Fig. 37). Disease is spread by insects and air borne conidia. Deep summer ploughing, separating sclerotial bodies from the seeds before sowing by steeping in saline solution, seed treatment with Thiram or Capton is recommended. In seed production plots, ensuring synchrony of flowering avoids the occurrence of ergot.

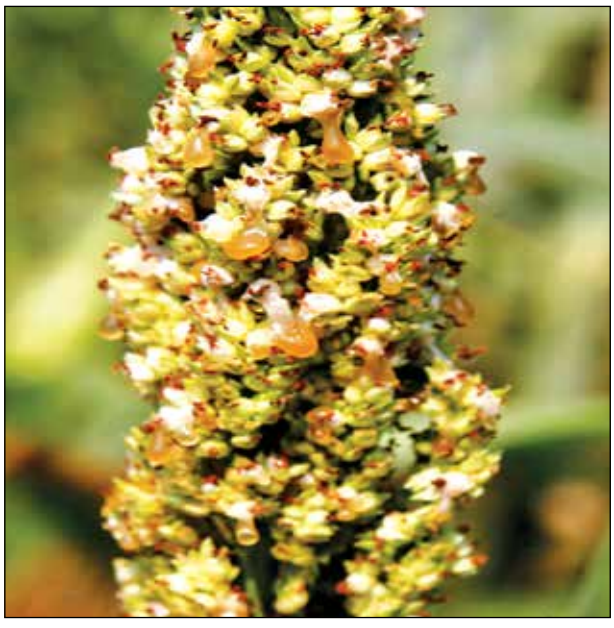


Fig.37: Ergot infestation Infested panicles at honey dew stage

6.2.7 Charcoal rot

Macrophomina phaseolina (Tassi) Goid

Lodging and poor grain-filling are the evident external symptoms. The fungus invades the crown via the roots and then proceeds to colonize and disorganize the cortical tissue of the lower internodes. The lower stem regions of the

Fig.38: Charcoal rot infestation a) Charcoal rot affected field; b) Internal symptoms of charcoal rot

infected plants become soft and hollow resulting in lodging (Fig 38a, b). Shredding dry pith with black sclerotical bodies is an important diagnostic symptom than other stalk rots. Losses in grain yield and seed size occur due to premature drying and lodging. Stunted growth and smaller stalks than normal, due to infection result in loss of quality and quantity of fodder. Minimal doses of nitrogen fertilizer and low plant densities reduce charcoal rot. Crop rotation also reduces the disease. Sorghum as a mixed crop also suffers less damage by charcoal rot than sole crop. Moisture conservation practices like wheat straw mulch will provide marginal advantage in checking the disease symptoms. Field sanitization and seed treatment with Carbendazim or Captan are recommended.

7. AGRONOMIC PRACTICES

Sorghum requires warm climate but can be grown under a wide range of climatic conditions. The plant can tolerate high temperatures throughout their life-cycle. The minimum temperature for germination of sorghum seed is 7-10°C. It needs 26-30°C temperature for its optimum growth. Though it can withstand temperatures up to 45°C, lower temperatures (<8°C) limit its cultivation owing to impaired flowering and pollination. Sorghum can grow from sea level to as high as 3,000 m elevation.

7.1 Soil

Sorghum can be grown successfully on a wide range of soils. In India, it is mainly grown in alfisols (red) and vertisols (black). It tolerates a pH range from 5.5 to 8.5 and also some degree of salinity, alkalinity, and poor drainage (Dogget, 1988). It will grow on heavy, deep-cracking vertisols and light sands (Hayward and Bernstein, 1958). In the tropics, sorghum tends to be grown on the heavier lands.

7.2 Sowing Season

In India, sorghum is grown in both monsoon (kharif) and post-monsoon (rabi) seasons. The optimum sowing time for kharif sorghum is last week of June to 1st week of July and for rabi sorghum is 3nd week of September to 1st week of October.

7.3 Soil Preparation

Deep ploughing once with mould board plough in summer followed by 3 to 4 harrowing is recommended to attain good seed bed and maintain weed free conditions in both kharif and rabi seasons. Making compartmental bunds of 10m x 20m during rabi season for soil moisture conservation helps in increasing yields.

7.4 Spacing and Transplanting

The optimum plant population varies from 1,50,000 to 2,00,000 plants/ha in irrigated kharif and rabi seasons and 1,35,000 plants/ha in rainfed rabi season. These plant populations are achieved by using 8-10 kg/ha seed with planting at 45 x 15 cm or 60 x 10 cm of row to row spacing and 15 cm of plant to plant spacing. After germination, plants in the rows are thinned at the desired spacing at two stages. First thinning should be done 10-15 days after emergence and the second at 20-25 days after sowing.

7.5 Manures and Fertilizers Required

Application of farm yard manure (organic source) has been the traditional practice in India. Ideally application of 10 tonnes/ha at the time of last ploughing is recommended. Sorghum under rainfed condition, 40-60 kg N/ha and 20-30 kg P_2O_5/ha is recommended as basal. Under irrigated conditions, 80-100 kg N/ha and 30-40 kg P_2O_5/ha is recommended as basal doses and in these condition P_2O_5 along with 50% N should be applied at sowing time and remaining half dose should be side-dressed at 30 days after sowing at flower primordial initiation stage. Seed inoculation with *Azotobacter chrooccum* or *Azospirillum lipoferum* has been found effective in 10-20 kg/ha N under rainfed conditions. The response to K fertilization in India is rare. The deficiency of zinc and iron (in calcareous soils) is increasing day by day. Soil application of 25 kg zinc sulphate once in 3 years or foliar spray (2 times) of 0.2% zinc sulphate is promising in zinc deficient soils. In case of iron deficiency, foliar spray (twice) of 0.1% ferrous sulphate is recommended.

7.6 Intercultural and Weed Control

Inter-cultivation 2 or 3 times at 3,5 and 7 weeks after sowing will helps in sufficient aeration, control weeds and conserve soil moisture by providing top soil mulch. If possible 1 or 2 hand weedings should be given to keep the crop free from weeds up to 30-40 days after sowing. As an alternative to hand weeding spraying of Atrazine @ 1 kg/ha in 800-1000 liter of water as pre-emergence just after sowing could successfully control the weeds. Another pre-emergence herbicide recommended for sorghum is prometryne @ 1 kg/ha. The integration of these herbicides with one hand weeding or hoeing at 35-40 DAS may effectively control most of the weeds. If striga menace is severe, 2, 4-D should be applied as post-emergence @ 1 kg/ha between 20-60 DAS, in addition to above herbicides

7.7 Harvest and Post-Harvest Practices

The sorghum crop should be harvested immediately after grain maturity. The right time for harvest is when grains become hard and contain less than 25% moisture. Generally 2 methods of harvesting i.e. stalk cut and cutting of earheads by sickles are adopted. However, in advanced countries, sorghum harvesters are used. In case of stalk cut method, the plants are cut from near the ground level. The stalks are tied into bundles of convenient sizes and stacked on the threshing floor. After 2-3 days, the earheads are removed from the plants. In other method, earheads only are removed from the standing crop and collected at the threshing floor for threshing after 3-4 days of sun-drying. Threshing of earheads is done either by beating them with sticks or by trampling under bullock feet. Threshing is also done with the help of

threshers. The threshed grain should be cleaned and dried in sun for 6-7 days to reduce the moisture content down to 13-15% for safe storage.

7.8 Seed Production

In India, the seed multiplication is four-stage generation system (nucleus seed, breeder seed, foundation seed, and certified seed). Nucleus seed is initial seed from selection of individual plants of a particular variety produced by breeder/institute. It is not covered under the purview of certification. Breeder seed is the progeny of nucleus seed and its production is organized by the ICAR through ICAR institutes, Agricultural Universities, and seed corporations on the basis of indents received from Department of Agriculture, Ministry of Agriculture, Government of India. Breeder seed production also does not comes under the purview of certification but its production and genetic purity is monitored by State and Central Seed Corporation.

Foundation seed is the progeny of breeder seed and it is genetically and physically pure. Certified seed is the progeny of foundation seed. For sorghum Maharashtra State Seed Corporation (MSSC), Andhra Pradesh State Seed Development Corporation (APSSDC) and Karnataka State Seed Corporation (KSSC) are the three major agencies that produce certified seed. The foundation and certified seed plots should be at least 400 m away from other sorghum types (Kannababu et al., 2004; Table 5). The maintenance breeding is also called as nucleus and breeder seed production, but it involves the purification of cytoplasmic male-sterile line (A-line), maintainer line (B-line), restorer line (R-line) and open pollinated variety.

Table 5. Prescribed isolation standards for production of different classes of sorghum seed

Contaminants	Minimum distance (m)	
	Foundation seed	Certified seed
Fields of other varieties	400	200
Fields of same variety but not confirming to purity	400	200
Johnsongrass (Sorghum halepense)	400	200
Forage sorghum with high tillering and grassy panicle	400	200

7.9 Seed Dormancy

Seed dormancy was reported in all types of sorghum as well as its wild species for at least one month (Gritton and Atkins, 1963; Harrington, 1916; Tester and McCormick 1954; Tao, 1982; Mott, 1978; Simpson, 2007). Seed coats having high content of inhibitory phenolic compounds and impermeability to water may be the major causal agent in the dormancy of sorghum (Harrington, 1923; Clark *et al.*, 1968) and on the other hand dormancy can be under metabolic control (Kamalavalli *et al.*, 1978).

8. BREEDING OBJECTIVES

8.1 Milestones in Breeding

Sorghum as a crop has been cultivated in India for centuries, owing to its better adaptability, assured grain and fodder yields, even in harsh climatic conditions. The objectives for sorghum breeding had been to enhance yield and quality of grain and stover for food and livestock use, biomass and stem sugar content for biofuel purposes (Reddy *et al.*, 2008).

The major milestones in sorghum breeding in India are (1) diversification of genetic base of cultivars using exotic germplasm, (2) Development of hybrid parents and release of hybrids to exploit heterosis for grain, fodder and biomass yields (3) Population improvement approach to augment the breeding material with desirable traits and alleles.

Sorghum is one of the first crops in which heterosis could be beneficially exploited in India. Commercial exploitation of heterosis has been possible owing to the availability of a stable and heritable CMS mechanism (Stephens and Holland, 1954), enabling large-scale, economic hybrid seed production and high magnitude of heterosis for economic traits. The hybrid programme in India was initiated in early 60s by attempting crosses of Indian tall cultivars as well as temperate dwarf parents as male parents on exotic CMS lines (CSH 1 to 4). With the breeding efforts in the Indian sorghum improvement program, improved and promising parental lines became available and were used to develop future set of hybrids (CSH 6 onwards) after 1975. From CSH 13 to the latest hybrid CSH 30, diversification of hybrids became a priority and traits such as earliness, grain size and mold tolerance were incorporated in new hybrids.

The multi-cut forage sorghum hybrid CSH 24MF provides for the highest forage yield (91 ton fresh forage/ha) coupled with superior forage quality (8% protein and 50% digestibility). Sweet sorghum cultivars with high stem sugar content were also identified and released. Notable ones are the varieties such as SSV 84 (high brix), CSV 24SS (High stalk and sugar yields) and hybrid CSH 22 SS (High stalk and sugar yields).

8.2 Advancements and Challenges

Breeding efforts of nearly 50 years have catapulted the yields of sorghum by many folds for both grain and fodder use. However, challenges remain in the areas of improving resistance to biotic and abiotic stresses, significant improvement in terms of nutritional quality, bioavailability, and consumer acceptability.

For the past several decades, several programs in India attempted to improve varieties and/or hybrid parents through pedigree breeding approach. More dramatic accruals in terms of grain yield and fodder/ biomass yield came through in the initial years and have reached a plateau thereafter. While the increase in productivity was possible by introgressing exotic material in kharif grain sorghum types, it resulted in greater susceptibility of the cultivars thus developed to biotic stresses and loss of consumer preference, in many instances. While complete immunity against major pests and diseases are not available, there is enough scope to build fair level of tolerance against most of these pests and diseases by conventional breeding and high resistance against grain mold and major pests by biotechnological approach and gene pyramiding. Genetic resistance in conjunction with other components of integrated plant protection management could offer lasting low cost solutions.

Increments in productivity were much slower in rabi-adapted cultivars compared to kharif-adapted ones (Kumar et al., 2010). Temperate photo-insensitive germplasm could not help development of rabi (post-rainy) cultivars of grain sorghum adapted to receding moisture conditions where local varieties (such as M35-1 that was released in 1937) are largely cultivated (Reddy et al., 2008; Rakshit et al., 2012). This calls for a change in breeding strategy, recombining adaptive and quality-associated traits of local varieties and grain and fodder yield potential of diverse but acceptable exotic or kharif material.

The advanced breeding programmes in forage breeding using diverse germplasm lines has resulted in more than doubling of forage yields in hybrids compared to varieties. However, absence of heterosis for biomass production had limited the progress in enhancement of forage yields of late. There is no easy answer to enhance forage production potential other than looking at diverse genetic backgrounds to yield more biomass or generate high heterosis for forage yield traits.

The only sweet sorghum hybrid CSH 22 SS released in the country is the bench mark for sweet sorghum productivity. There is a need to develop newer cultivars that produce high stalk yield and more energy in different agro-climatic areas of the country. They should also possess resistance/tolerance to various stresses and should be of staggered maturity times to widen the harvest window, ensuring continuous supply of feed stock to the sweet sorghum processing plants (Reddy et al., 2005). Any increase in biomass resulting from these breeding programmes would also ensure an important role for sweet sorghum as both first and second generation biofuel.

9. BIOTECHNOLOGICAL INTERVENTIONS IN SORGHUM

Sorghum is the C4 food crop for which complete genome sequence available and the complete genome sequencing of sorghum genotype Btx 623 estimated the genome size as 730 Mb and the GC content is estimated at 37.7%. In sorghum heterochromatin occupies at least 460 Mb and 252 Mb is euchromatin. The sorghum genome contains 55% retrotransposons, 7.5% of DNA transposons and 1.7% of miniature inverted-repeat transposable elements. Approximately 27,640 protein coding genes found in sorghum followed by 5,197 genes contain less than 150 amino acids have few exons and 727 processed pseudogenes. A total of 67 known micro RNAs (miRNAs) and 82 additional miRNAs identified in sorghum genome (Peterson *et al.*, 2002; Paterson *et al.*, 2009).

Cytogenetic maps of sorghum chromosomes were constructed on the basis of the fluorescence in situ hybridization (FISH) using BACs. BTx623 an elite inbred line was used to estimate the molecular size of the each chromosome and established a generally accepted size based nomenclature for sorghum chromosomes (SBI-01 to SBI-10) and linkage groups (LG-01 to LG-10) (Kim *et al.*, 2005a; Kim *et al.*, 2005b).

A single consensus genetic map of sorghum constructed by using six component mapping populations to integrate over 2000 unique loci including 1182 unique DArT markers. The distinct genetic maps that contains commonly utilized SSR, AFLP, RFLP and high throughput DArT markers to obtain a general order and distances for a greater number of markers and to obtain more complete coverage of the sorghum genome (Mace *et al.*, 2009).

The first QTL studies in sorghum in 1995 (Lin et al., 1995; Paterson et al., 1995a, 1995b; Pereira et al., 1995; Pereira and Lee, 1995) after that more number of QTLs identified in sorghum for more than 150 traits using around 30 unique mapping populations (Mace and Jordon, 2011). Mace

and Jordon (2011) integrated sorghum whole genome sequence information with a compendium of sorghum QTL studies with a total of 771 individual QTL from 44 studies related to 161 unique traits from eight broad trait categories with a population size ranged from 85 to 378 (Table 6). The study revealed that 169 QTLs related to the trait category stem morphology, 128 to biotic stress resistance, 121 QTL to grain, 93 to abiotic stress resistance, 62 to maturity, 96 to stem composition, 56 to panicle, and 46 to the trait category leaf. The average size of the projected QTL was 11.5 cM.

Genetic engineering of sorghum has emerged as an al¬ternative tool for the introduc¬tion of desirable traits into elite varieties. Three different methods of genetic transformation have been reported in sorghum viz., protoplast mediated (Ou-Lee *et al.*, 1986; Battraw and Hall, 1991) particle bombardment (Casas *et al.*, 1993; Able *et al.*, 2001; Emani et al., 2002; Jeoung *et al.*, 2002; Tadesse *et al.*, 2003; Girijashankar *et al.*, 2005; Grootboom et al., 2010; Anshu *et al.*, 2010; Guoquan Liu and Godwin, 2012; Visarada *et al.*, 2014) and Agrobacterium mediated transformation (Zhao *et al.*, 2000; Gao *et al.*, 2005; Howe *et al.*, 2006; Nguyen *et al.*, 2007; Gurel *et al.*, 2009; Shridhar *et al.*, 2010; Kumar *et al.*, 2011). Only a few reports on development of transgenic sorghum using agronomically important genes such as rice chitinase that confers resistance against stalk rot (Zhu *et al.*, 1998; Krishnaveni *et al.*, 2001), Bt genes (*cry1Aa, cry1Ac, cry1Ab, cry1B*) for resistance to stem borer (Girijashankar et al., 2005; Zhang *et al.*, 2009; Visarada et al., 2014), expression of rice OsCDPK-7 gene to enhance abiotic stress tolerance (Tejinder *et al.*, 2011) and *mtlD* gene encoding for mannitol-1-phosphate dehydrogenase from *E. coli* to enhance tolerance to water deficit and NaCl stress (Maheswari *et al.*, 2010).

Table 6. Detailed list of QTL publications in sorghum

Reference	Population pedigree	Generation	Population size	No. of loci mapped	No. of LGs	Map length	Marker density
Agrama *et al.* (2002)	GBIK/ Redlan	RI	93	113	12	1530	13.5398
Brown *et al.* (2006)	BTx623/IS3620C	RI	137	396	10	127.8	3.22929
Brown *et al.* (2008)	Association panel	377	57	10	-	-	-
Chantereau *et al.* (2001)	IS2807/ IS7680	RI	85	129	12	878	-
Crasta *et al.* (1999)	B35/Tx430	RI	96	128	14	1602	-
Deu *et al.* (2005)	Malisor84-7/ S34	F2	217	92	13	1160	12.6087
Feltus *et al.* (2006)	BTx623/IS3620C	RI	137	145	10	-	-
Feltus *et al.* (2006)	BTx623/ *S. propinquum*	F2	370	96	10	-	-
Hart *et al.* (2001)	BTx623/IS3620C	RI	137	145	10	1278.8	8.81931
Haussmann *et al.* (2002)	IS9830/E36-1	RI	226	128	10	1291.2	10.0875
Haussmann *et al.* (2002)	N13/E36-1	RI	226	146	12	1438.1	9.85
Haussmann *et al.* (2004)	IS9830/E36-1	RI	226	157	11	1599	10.1847
Haussmann *et al.* (2004)	N13/E36-1	RI	226	157	11	1599	10.1847
Katsar *et al.* (2002)	BTx623/ *S. propinquum*	F3	370	-	-	-	-
Katsar *et al.* (2002)	RTx430/PI550607	F3	195	-	-	-	-
Kebede *et al.* (2001)	SC56/Tx7000	RI	125	144	10	1355	9.40972

Kim (2003)	BTx623/IS3620C	RI	137	-	-	-	-
Klein *et al.* (2001)	RTx430/Sureno	RI	125	130	10	970	7.46154
Knoll *et al.* (2008)	Shan Qui Red/ SRN39	RI	153	132	14	2128	16.1212
Lin *et al.* (1995)	BTx623/ *S. propinquum*	F2	370	78	11	935	11.9872
Mohan *et al.* (2009)	296B/IS18551	RI	168	96	-	-	-
Murray *et al.* (2008a)	BTx623/Rio	RI	176	259	10	1836	7.0888
Murray *et al.* (2008b)	BTx623/Rio	RI	176	259	10	1836	7.0888
Nagaraj *et al.* (2005)	96-4121/ Redlan	RI	88	60	13	603.5	10.0583
Nagy *et al.* (2007)	Shan Qui Red/ Colby	F3	178	-	-	-	-
Parh *et al.* (2005)	R939145-2-2/ IS8525	RI	146	286	15	1599.1	5.59126
Parh *et al.* (2008)	R939145-2-2/ IS8525	RI	146	305	10	1625.2	5.32852
Paterson *et al.* (1995a)	BTx623/ *S. propinquum*	F2	370	78	11	1020	13.0769
Paterson *et al.* (1995b)	BTx623/ *S. propinquum*	F2	370	78	11	1020	13.0769
Paterson *et al.* (1995b)	BTx623/ *S. propinquum*	BC1	378	-	-	-	-
Pereira and Lee (1995)	CK60/ PI229828	F2	152	111	10	1299	11.7027
Pereira *et al.* (1995)	CK60/ PI229828	F2	152	111	10	1299	11.7027
Perumal *et al.* (2009)	SC748-5/BTx623	F2	146	98	-	-	-
Rami *et al.* (1998)	IS2807/379	RI	110	128	11	878	6.85938
Rami *et al.* (1998)	IS2807/249	RI	90	151	11	977	6.4702
Ritter *et al.* (2008)	R9188/ R9403463-2-1	RI	184	228	16	1879.2	8.24211
Salas Fernandez *et al.* (2008)	KS115/Macia	RI	351	112	11	1364.6	12.1839
Satish *et al.* (2009)	296B/IS18551	RI	168	162	16	1143	7.05556
Shiringani *et al.* (2010)	M71/SS79	RI	188	157	11	1029	6.55414
Srinivas *et al.* (2009)	296B/IS18551	RI	168	152	15	1098.7	7.22829
Srinivasa Reddy *et al.* (2008)	IS22380/E36-1	RI	93	85	10	650.3	7.65059
Subudhi *et al.* (2000)	B35/Tx7000	RI	98	232	10	-	-
Tao *et al.* (1998)	QL39/QL41	RI	160	166	21	1400	8.43373
Tao *et al.* (2000)	QL39/QL41	RI	160	311	10	2750	8.84244
Tao *et al.* (2003)	ICSV745/ B890562	RI	120	264	12	1472	5.57576
Tuinstra *et al.* (1997)	Tx7078/B35	RI	98	170	17	1645	9.67647
Winn *et al.* (2009)	P850029/Sureno	F4	277	8	1	61.5	7.6875
Wu and Huang (2008)	Westland A/ PI550610	F2	277	118	10	1005	8.51695
Wu *et al.* (2007)	Westland A/ PI550610	F2	233	118	16	1000	8.47458
Xu *et al.* (2000)	B35/Tx7000	RI	98	145	10	835	5.77241

10. REFERENCES

Abdelgadir M, Abbas M, Järvi A, Elbagir M, Eltom M, Berne C (2005) Glycaemic and insulin responses of six traditional Sudanese carbohydrate-rich meals in subjects with Type 2 diabetes mellitus. Diabetic Medicine 22:213-217.

Able JR, Rathus C, Godwin ID (2001) The investigation of optimal bombardment parameters for transient and stable transgene expression in sorghum. In Vitro Cell Dev Biol-Plant 37:341-348.

Agrama HA, Widle GE, Reese JC, Campbell LR, Tuinstra MR (2002) Genetic mapping of QTLs associated with greenbug resistance and tolerance in Sorghum bicolor. Theor Appl Genet 104:1373-1378.

Aldrich PR, Doebley J (1992) Restriction fragment variation in the nucleus and chloroplast genomes of cultivated and wild *Sorghum bicolor.* Theor Appl Genet 85:293-302.

Ali ML, Rajewski JF, Baenziger PS, Gill KS, Eskridge KM, Dweikat I (2008) Assessment of Genetic Diversity and Relationship among a Collection of US Sweet Sorghum Germplasm by SSR Markers. Mol Breed 21:497-509.

Al-Suwaiegh S, Fanning KC, Grant RJ, Milton CT, Klopfenstein TJ (2002) Utilization of Distillers Grains from the Fermentation of Sorghum or Corn in Diets for Finishing Beef and Lactating Dairy Cattle. J Anim Sci 80:1105-1111.

Andersson MS, M Carmen de Vicente (2010) Gene flow between crops and their wild relatices. The Johns Hopkins University Press.

Anshu R, Robert GB (2010) Genetic transformation of sweet sorghum. Plant Cell Rep 29:997-1005.

Arriola PE, Ellstrand NC (1996) Crop-to-weed gene flow in the genus Sorghum (Poaceae): Spontanious interspecific hybridization between Johnsongrass, *Sorghum halepense* and crop sorghum, *S. bicolor.* Am J Bot 83:1153-1159.

Arriola PE, Ellstrand NC (2002) Gene flow and hybrid fitness in the *Sorghum bicolor-Sorghum halepense* complex. In: Snow AA (ed.) methods Workshop: Ecological and Agronomic Consequences of Gene Flow from Transgenic Crops to Wild Relatives; meeting Proceedings, University Plaza Hotel and Conference center, Ohio State University, Columbus, Ohio, March 5-6, 2002, pp :25-30.

Artschwager ER, McGuire C (1949) Cytology of reproduction in *Sorghum vulgare.* J Agri Res 78:659-673.

Arya L, Verma M, Sandhia GS, Singh SK, Lakhanpaul S (2008) Pattern of genetic relationship as revealed by AFLP markers in Indian sorghum [*Sorghum bicolor* (L.) Moench]. Ind J Genet Plant Breed 68:139-144.

Ayana A, Bekele E, Bryngelsson T (2000a) Genetic variation in wild sorghum (*Sorghum bicolor* ssp. Verticilliflorum L. Moench) germplasm from Ethiopia assessed by random amplified polymorphic DNA (RAPD). Hereditas 132:249-254.

Ayana A, Bryngelsson T and Bekele E (2000b) Genetic variation of Ethiopian and Eritrean sorghum (*Sorghum bicolor* L. Moench) germplasm assessed by random amplified polymorphic DNA (RAPD). Genet Resour Crop Evol 47:471-482.

Aydin G, Grant RJ, O'Rear J (1999). Brown Midrib Sorghum in Diets for Lactating Dairy Cows. J. Dairy Sci 82:2127-2135.

Ayyangar GNR, Rao VP (1931) Studies in sorghum: I anthesis and pollination. Ind J Agric Sci 1:445-454.

Baker HG (1972) Human influence on plant evolution. Econ Bot 26:32-43.

Barnaud A, Trigueros G, McKey D, Joly H (2008) High outcrossing rates in fields with mixed sorghum landraces: how are landraces maintained?. Heredity 101:445-452.

Battraw M, Hall TC (1991) Stable transformation of *Sorghum bicolor* protoplasts with chimeric neomycin phosphotransferase II and-glucuronidase genes. Theor Appl Genet 82:161-168.

Billot C, Ramu P, Bouchet S, Chantereau J, Deu M, Gardes L, Noyer JL, Rami JF, Rivallan R, Li Y, Lu P, Wang T, Folkertsma RT, Arnaud E, Upadhyaya HD, Glaszmann JC, Hash CT (2013) Massive sorghum collection genotyped with SSR markers to enhance use of global genetic resources. PLoS ONE 8(4):e59714.

Billot C, Rivallan R, Sall MN, Fonceka D, Deu M, Glaszmann JC, Noyer JL, Rami JK, Risterucci AM, Wincker P, Ramu P, Hash CT (2012) A reference microsatellite kit to assess for genetic diversity of *Sorghum bicolor* (Poaceae). Am J Bot 6:245-260.

Bouchet S, Pot D, Deu M, Rami JF, Billot C, Perrier X, Rivallan R, Gardes L, Xia L, Wenzl P, Kilian A, Glaszmann JC (2012) Genetic structure, linkage disequilibrium and signature of selection in sorghum: lessons from physically anchored DArT markers. PLoS One 7(3):e33470.

Bourne BA (1935) A comparative study of certain morphological characters of sugarcane x sorgo hybrids. J Agric Res 50:539-552

Brooking IR (1979) Male sterility in *Sorghum bicolor* (L.) Moench induced by low night temperature. II. Genotypic differences in sensitivity. Aus J Plant Physiol 6:143-147.

Brown PJ, Klein PE, Bortiri E, Acharya CB, Rooney WL, Kresovich S (2006) Inheritance of inflorescence architecture in sorghum. Theor Appl Genet 113:931-942.

Brown PJ, Rooney WL, Franks C, Kresovich S (2008) Efficient mapping of plant height quantitative trait loci in a sorghum association population with introgressed dwarfing genes. Genetics 180:629-637.

Brown SM, Hopkins MS, Mitchell SE, Wang TY, Kresovich S, Duncan RR, Senior ML, Gonzalez-Candelas F (1996) Multiple methods for the identification of polymorphic simple sequence repeats in sorghum [*Sorghum bicolor* (L.) Moench]. Theor Appl Genet 93:190-198.

Casa AM, Mitchell SE, Hamblin MT, Sun H, Bowers JE, Peterson AH, Aquadro CF, Kresovich S (2005) Diversity and selection in sorghum: simultaneous analyses using simple sequence repeats. Theor Appl Genet 111:23-30.

Casas AM, Kononowicz AK, Zehr UB, Tomes DT, Axtell JD, Butler LG, Bressan RA, Hasegawa PM (1993) Transgenic sorghum plants via microprojectile bombardment. Proc Natl Acad Sci (USA) 90:11212-11216.

Celarier RP (1958) Cytotaxonomic notes on the subsection halepensia of the genus Sorghum. Bull Torr Bot Club 85:49-62.

Celarier RP (1959) Cytotaxonomy of the Andropogonea. III. Sub-tribe sorgheae, genus, sorghum. Cytologia 23:395-418.

Chandel AS, Saxena SC, Singh K (1995) Integrated weed control and its economics in soybean (Glycine max) grown in mollisols of Uttar Pradesh. Ind J Agron 40:228-234.

Chantereau J, Trouche G, Rami JF, Deu M, Barro C, Grivet L (2001) RFLP mapping of QTLs for photoperiod response in tropical sorghum. Euphytica 120:183-194.

Cheema ZA, Khaliq A (2000) Use of sorghum allelopathic properties to control weeds in irrigated wheat in a semiarid region of Punjab. Agric Ecosyst Envir 79:105-112.

Cheema ZA, Luqman M, Khaliq A (1997) Use of allelopathic extracts of sorghum and sunflower herbage for weed control in wheat. J Anim Plant Sci. 7:91-93.

Ciacci C, Maiuri L, Caporaso N, Bucci C, Del Giudice L, Rita Massardo D, Pontieri P, Di Fonzo N, Bean SR, Ioerger B, Londei M (2007) Celiac disease: In vitro and in vivo safety and palatability of wheat-free sorghum food products. Clin Nutr 26:799-805.

Clark LE, Collier JW, Langston R (1968) Dormancy in *Sorghum bicolor* (L.) Moench. 11. Effects of pericarp and testa. Crop Sci 8:115-158.

Clay BR, Edwards WC, Peterson DR (1976) Toxic nitrate accumulation in the sorghums. Bovine Pract 11:28-32.

Clayton WD (1961) Proposal to conserve the generic name Sorghum Moench (Gramineae) versus sorghum adans (Gramineae). Taxonomy 10:242-243.

Crasta OR, Xu WW, Nguyen HT, Rosenow DT, Mullet J (1999) Mapping of post flowering drought resistance traits in grain sorghum: association between QTLs influencing premature senescence and maturity. Mol Gen Genet 262:579-588.

Cui YX, Xu GW, Magill CW, Schertz KF, Hart GE (1995) RFLP-based assay of Sorghum bicolor (L.) Moench genetic diversity. Theor Appl Genet 90:787-796.

D'je Y, Heuertz M, Ater M, Lefebyre C, Vekemans X (2004) In situ estimation of outcrossing rate in sorghum landraces using microsatellite markers. Euphytica 138:205-212.

Dahlberg (2000) Classification and characterization of Sorghum: weed and their control in grain sorghum. In: Smith CW and Frederiksen RA (cds.) Sorghum: Origin, History, Technology, and Production, John Wiley and Sons: New York, USA, pp:99-130.

Damania AB (1980) The Hindustani centre of origin of important plants. Asian Agric History 6:333-341.

Dayakar Rao B, Patil JV, Reddy KN, Soni VK and Srivastsava G (2014) SORGHUM An Emerging Cash Crop. Cambridge University press India Ltd.

de Wet JMJ (1977) Domestication of African cereals. Afr Econ Hist 3:15-32.

de Wet JMJ (1978) Systematics and evolution of Sorghum sect. Sorghum (Gramineae). Am J Bot 65: 477-484.

de Wet JMJ, Harlan JR (1971) The origin and domestication of *sorghum bicolor*. Econ Bot 25: 128-135.

de Wet JMJ, Gupta SC, Harlan JR, Grassl CO (1976) Cytogenetics of introgression from Saccharum into Sorghum. Crop Sci 16:568-572.

Del Pozo-Insfran D, Urias-Lugo D, Hernandez-Brenes C, Serna-Saldivar SO (2004) Effect of Amyloglucosidase on Wort Composition and Fermentable Carbohydrate Depletion in Lager Beers. J Inst Brew 110:124-132.

Deu M, Gonzalez-de-Leon D, Glazsmann JC, Degremont I, Chantereau J, Lanaud C, Hamon P (1994) RFLP diversity in cultivated sorghum in relation to racial differentiation. Theor Appl Genet 88:838-844.

Deu M, Ratnadass A, Hamada MA, Noyer JL, Diabate M, Chantereau J (2005) Quantitative trait loci for head-bug resistance in sorghum. Afr J Biotechnol 4:247-250.

Deu M, Rattunde F, Chantereau J (2006) A global view of genetic diversity in cultivated sorghums using core collection. Genome 49:168-180.

Deu M, Sagnard F, Chantereau J, Calatayud C, Herault D, Mariac C, Pham JL, Vigouroux Y, Kapran I, Traore PS, Mamadou A, Gerard B, Ndjeunga J, Bezancon G (2008) Niger- wide assessment of in situ sorghum genetic diversity with microsatellite markers. Theor Appl Genet 116:903-913.

Dillon SL, Shapter FM, Henry RJ, Cordeiro G, Izquierdo L, Slade LL (2007) Domestication to Crop Improvement: Genetic Resources for Sorghum and Saccharum (Andropogoneae). Ann Bot 100:975-989.

Doggett E (1988) Sorghum. John Wiley & Sons, Inc., New York, NY, USA.

Doggett H, Majisu BN (1968) Disruptive selection in crop development. Heredity 23:1-23.

Doggett H, Prasada Rao KE (1995) Sorghum: In Evolution of crop plants (Smartt J and Simmonds NW, eds.). UK: Longman, Harlow pp:173-180.

Dweikat I (2005) A diploid, interspecific, fertile hybrid from cultivated sorghum, *Sorghum bicolor*, and the common Johnsongrass weed Sorghum halepense. Mol Breed 16: 93-101.

Eastin JD (1972) Photosynthesis and translocation in relation to plant development. In: Sorghum in Seventies (Eds. NGP Rao and LR House), Oxford and IBH Publishing Co., New Delhi, India pp:214-246.

Eberhart SA, Bramel-Cox PJ, Prasada Rao KE (1997) Preserving genetic resources. In Proceedings of the International Conference on Genetic Improvement of Sorghum and Pearl Millet, 22-27 September 1996, Lubbock, TX, pp:25-41.

Ejeta G, Grenier C (2005) Sorghum and its weedy hybrids. In Crop Ferality and Volunteerism, Gressel, J, ed CRC Press, Taylor and Francis Group, USA pp:123-135.

Elangovan M, Kiran Babu P, Tonapi VA, Subba Rao LV, Sivaraj N (2012) Cultivated Grasses and their Wild Relatives in Andhra Pradesh and Their Conservation Concerns. Ind J Plant Genet Resour 25:166-173.

Ellstrand NC, Foster F (1983) Impact of population structure on the apparent outcrossing rate of grain sorghum (*Sorghum bicolor*). Theor Appl Genet 66:323-327.

Emani C, Sunilkumar G, Rathore KS (2002) Trans gene silencing and reactivation in sorghum. Plant Sci 162:181-192.

Endrizzi JE (1957) Cytological studies of some species and hybrids in the Eu-sorghums. Bot Gaz 119:1-10.

FAOSTAT (2013) http://faostat.fao.org.

Farrar JL, Hartle DK, Hargrove JL, Greenspan P (2008) A novel nutraceutical property of select sorghum (*Sorghum bicolor*) brans: inhibition of protein glycation. Phytother Res 22:1052-1056.

Feltus FA, Hart GE, Schertz KF, Casa AM, Kresovich S, Abraham S, Klein PE, Brown PJ, Paterson AH (2006) Alignment of genetic maps and QTLs between inter- and intraspecific sorghum populations. Theor Appl Genet 112:1295-1305.

Figueroa JDC, Martinez BF, Rios E (1995) Effect of Sorghum Endosperm Type on the Quality of Adjuncts for the Brewing Industry. J Am Soc Brew Chem 53:5-9.

Ganapathy KN, Gomashe SS, Rakshit S, Prabhakar B, Ambekar SS, Ghorade RB, Biradar BD, Saxena U, Patil JV (2012) Genetic diversity revealed utility of SSR markers in classifying parental lines and elite genotypes of sorghum (*Sorghum bicolor* L. Moench). Aust J Crop Sci 6: 1486-1493.

Gao Z, Xie X, Ling Y, Muthukrishnana S, Liang GH (2005) Agrobacterium tumefaciens-mediated sorghum transformation using a mannose selection system. Plant Biotechnol J 3:591-599.

Garber ED (1950) Cytotaxonomic studies in the genus Sorghum. University of California Publications in Botany 23:283-361.

Ghebru B, Schmidt RJ, Bennetzen JL (2002) Genetic diversity of Eritrean sorghum landraces assessed with simple sequence repeat (SSR) markers. Theor Appl Genet 105:229-236.

Gibbons WR, CA Westby, TL Dobbs (1986) Intermediate-scale, Semi-continuous Solid-phase Fermentation Process for Production of Fuel Ethanol from Sweet Sorghum. Appl Environ Microbiol 51:115-122.

Girijashankar V, Sharma HC, Sharma KK, Swathisree V, Sivarama Prasad L, Bhat BV, Royer M, Secundo BS, Narsu ML, Altosaar I, Seetharama N (2005) Development of transgenic sorghum for insect resistance against the spotted stem borer (Chilo partellus) Plant Cell Rep 24:513-522.

Gomez-Cordoves C, Bartolome B, Vieira W and Virador VM (2001) Effects of wine phenolics and sorghum tannins on tyrosinase activity and growth of melanoma cells. J Agric Food Chem 49:1620-1624.

Gopal Reddy GN, Rao Kameshwara, Reddy BVS and Prasada Rao KE (2002) Geographic distribution of basic and intermediate races in the world collection of sorghum germplasm. Int Sorghum and Millets Newsl 43:15-17.

Gour TB, Sriramulu M, Ramesh Babu T, Reddy DDR, Chandrasekhara Rao K, Narayan Reddy P, Ravindra Babu R (2000) Millets. Insect pests, diseases, nutritional disorders. Information Bulletin No. 15, Acharya N.G. Ranga Agricultural University, Hyderabad, India.

Gray E, Rice JS, Wattenbarger D, Benson JA, Hester AJ, Loyd RC, Greene BM (1968). Hydrocyanic acid potential of Sorghum plants grown in Tennessee. University of Tennessee Agricultural Experiment Station, Bulletins. http://trace.tennessee.edu/utk_agbulletin/156.

Grimmer HR, Parbhoo V, McGrath RM (1992) Antimutagenicity of polyphenol-rich fractions from *sorghum bicolor* grain. J Sci Food Agric 59:251-256.

Gritton ET, Atkins RE (1963) Germination of sorghum seed as affected by dormancy. Agron J 55:169-174.

Grootbroom AW, Mkhonza NL, Kennedy O, Chakuya E, Kurent K and Chikwamba RK (2010) Biolostic mediated Sorghum transformation via Mannose and Bialaphos based selection system. Int J Botany 6(2):89-94.

Guoquan Liu, Godwin ID (2012) Highly efficient sorghum transformation, Plant Cell Rep 31:999-1007.

Gurel S, Gurel E, Kaur R, Wong J, Meng L, Tan HQ, Lemaux PG (2009) Efficient, reproducible Agrobacterium-mediated transformation of sorghum using heat treatment of immature embryos. Plant Cell Rep 28:429-444.

Hadley HH (1953) Cytological relationship between Sorghum vulgare and Sorghum halepense. Agron. J 45:139-143.

Harlan JR (1971) Agricultural origins: centers and non-centers. Sceience 174:568-574.

Harlan JR (1975) Crops and Man. American Society of Agronomy, Madison, WI.

Harlan JR, de Wet JMJ (1972) A simplified classification of cultivated sorghum. Crop Sci 2:172-176.

Harrington GT (1916) Germination and viability tests of Johnson grass seed. Proc Assoc Off Seed Anal 9:24-28.

Harrington GT (1923) Use of alternating temperatures in the germination of seeds. J Agric Res 23: 295-332.

Hart GE, Schertz KF, Peng Y, Syed NH (2001) Genetic mapping of *Sorghum bicolor* (L.) Moench QTLs that control variation in tillering and other morphological characters. Theor Appl Genet 103:1232-1242.

Haussmann BIG, Hess DE, Omanya GO, Folkertsma RT, Reddy BVS, Kayentao M, Welz HG, Geiger HH (2004) Genomic regions influencing resistance to the parasitic weed Striga hermonthica in two recombinant inbred populations of sorghum. Theor Appl Genet 109:1005-1016.

Haussmann BIG, Mahalakshmi V, Reddy BVS, Seetharama N, Hash CT, Geiger HH (2002) QTL mapping of stay-green in two sorghum recombinant inbred populations. Theor Appl Genet 106:133-142.

Hayward HE, Bernstein L (1958) Plant-growth relationships on salt-affected soils. Bot Rev 24:584-635.

Holm LG, Plucknett DL, Pancho JV, Herberger JP (1977) The world's worst weeds: distribution and biology, University Press of Hawaii, Honolulu pp:54-61.

House LR (1985) A Guide to Sorghum Breeding (2nd ed.). Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Howe A, Sato S, Dweikat I, Fromm M, Clemente T (2006) Rapid and reproducible Agrobacterium-mediated transformation of sorghum. Plant Cell Rep 25:751-758.

Hulse JH, Liang EM, Pearson OE (1980) Sorghum and the Millets: their composition and nutritional value. London, Academic Press.

ICRISAT (1992) The medium term plan. International Crops Research Institute for Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India.

Immelman K, Eardley C (2000) Gathering of grass pollen by solitary bees (halictidae, Lipotriches) in South Africa. Mitt Mus Naturk Berlin Zool Reihe 76:263-268.

Janakiammal EK, Singh TSN (1936) Preliminary note on a new Saccharum x sorghum hybrid. Ind J Agric Sci 6:1105-1106.

Jeoung JM, Krishnaveni S, Muthukrishnan S, Trick HN, Liang GH (2002) Optimization of sorghum transformation parameters using genes for green fluorescent protein and - glucuronidase as visual marker. Heriditas 137:20-28.

Jeya Prakash SP, Biji KR, Michael Gomez S, Ganesa Murthy K, Chandra Babu R (2006) Genetic diversity analysis of sorghum (*Sorghum bicolor* L. Moench) accessions using RAPD markers. Ind J Crop Sci 1:109-112.

Kamalavalli D, Amine JV, Pathak CJ, Sen DJ, Bansal RP (1978) The cyanide induced early germination of sorghum. In Environment and Physiological Ecology of Plants, ed. D.N. Sen and R.P. Bansal, Dehra Dun, India pp:67-76.

Kannababu N, Tonapi VA, Seetharama N (2004). Seed production manual. National Research Center for Sorghum, Rajendranagar, Hyderabad 500 030, Andhra Pradesh, India.

Katsar CS, Paterson AH, Teetes GL, Peterson GC (2002) Molecular analysis of Sorghum resistance to the greenbug (Homoptera: Aphididae). J Econ Entomol 95:448–457.

Kebede H, Subadhi PK, Rosenow DT, Nguyen HT (2001) Quantitative trait loci influencing drought tolerance in grain sorghum (*Sorghum bicolor* L. Moench). Theor Appl Genet 103:266-276.

Kim J (2003) Genomic Analysis of sorghum by fluorescence in situ hybridization. PhD thesis. Texas A&M University.

Kim J, Klein PE, Klein RR, Price HJ, Mullet JE, Stelly DM (2005a) Chromosome identification and nomenclature of *Sorghum bicolor*. Genetics 169:1169-1173.

Kim JS, Islam-Faridi MN, Klein PE, Stelly DM, Price HJ, Klein RR, Mullet JE (2005b) Comprehensive molecular cytogenetic analysis of sorghum genome architecture: distribution of euchromatin, heterochromatin, genes and recombination in comparison to rice. Genetics 171:1963-1976.

Kingsbury JM (1964) Poisonous plants of the United States and Canada. Prentice-Hall Inc., Englewood Cliffs, N.J., USA pp:626.

Klein RR, Rodriguez-Herrera R, Schlueter JA, Klein PE, Yu ZH, Rooney WL (2001) Identification of genomic regions that affect grain-mould incidence and other traits of agronomic importance in sorghum. Theor Appl Genet 102:307-319.

Knoll J, Gunaratna N, Ejeta G (2008) QTL analysis of early-season cold tolerance in sorghum. Theor Appl Genet 116:577-587.

Krishnaveni S, Jeoung JM, Muthukrishnan S, Liang GH (2001) Transgenic sorghum plants constitutively expressing a rice chitinase gene show improved resistance to stalk rot. J Genet Breed 55:151-158.

Kuhlman LC, Burson BL, Klein PE, Klein RR, Stelly DM, Price HJ, Rooney WL (2008) Genetic recombination in *Sorghum bicolor* x S. macrospermum interspecific hybrids. Genome 51(9):749-56.

Kumar CVS, Shreelakshmi CH, Shivani D (2010) Genetic diversity analysis in rabi sorghum (*Sorghum bicolor* (L.) Moench) local genotypes. Electro J Plant Breed 1(4):527-529.

Kumar V, LeAnne M. Campbell, Keerti SR (2011) Rapid recovery and characterization of transformants following Agrobacterium-mediated T-DNA transfer to sorghum. Plant Cell Tiss Organ Cult 57:147-154.

Lakshmi KB, Vimala V (1996) Hypoglycemic effect of selected sorghum recipes. Nutri Res 16: 1651-1658.

Lansac AR, Sullivan CY, Johnson BE, Lee KW (1994) Viability and germination of the pollen of sorghum (*Sorghum bicolor* (L.) Moench). Ann Bot 74:27-33.

Laopaiboon L, Thanonkeo P, Jaisil P, Laopaiboon P (2007) Ethanol production from sweet sorghum juice in batch and fed-batch fermentations by Saccharomyces cerevisiae. World J Microbiol Biotechnol 23(10):1497-1501.

Laurie D, Bennett MD (1989) Genetic variation in Sorghum for the inhibition of maize pollen tube growth. Ann Bot 64:675-681.

Lazarides M, Hacker JB, Andrew MH (1991) Taxonomy, cytology and ecology of indigenous Australian sorghums (Sorghum Moench: Andropogoneae: Poaceae). Aust Syst Bot 4:591-635.

Lin YR, Schertz KF, Paterson AH (1995) Comparative analysis of QTLs affecting plant height and maturity across the Poaceae, in reference to an interspecific sorghum population. Genetics 141:391-411.

Linnaeus C (1753) Species Plantarurn, Stockholm.

Lodge SL, Stock SL, Klopfenstein TJ, Shain DH, Herold DW (1997) Evaluation of Corn and Sorghum Distillers By-products. J. Anim Sci 75:37-43.

Mace ES, Jordan DR (2011) Integrating sorghum whole genome sequence information with a compendium of sorghum QTL studies reveals uneven distribution of QTL and of gene-rich regions with significant implications for crop improvement. Theor Appl Genet 123:169-191.

Mace ES, Rami JF, Bouchet S, Klein PE, Klein RR, Kilian A, Wenzl P, Xia L, Halloran K, Jordan DR (2009) A consensus genetic map of sorghum that integrates multiple component maps and high-throughput Diversity Array Technology (DArT) markers. BMC Plant Biol 9:13.

Mace ES, Xia L, Jordan DR, Halloran K, Parh DK, Huttner E, Wenzl P, Kilian A (2008) DArT markers: diversity analyses and mapping in *Sorghum bicolor*. BMC Genomics 9:26.

Madhusudhana R, Balakrishna D, Rajendrakumar P, Seetharama N, Patil JV (2012) Molecular characterization and assessment of genetic diversity of sorghum inbred lines. Afr J Biotechnol 11:15626-15635.

Maheswari M, Varalaxmi Y, Vijayalakshmi A, Yadav SK, Sharmila P, Venkateswarlu B, Vanaja M, Parshasaradhi P (2010) Metabolic engineering using mtlD gene enhances tolerance to water deficit and salinity in sorghum. Biol Plant 54:647-652.

Makokha AO, Oniang'o RK, Njoroge SM, Kamar OK (2002) Effect of traditional fermentation and malting on phytic acid and mineral availability from sorghum (*Sorghum bicolor*) and finger millet (Eleusine coracana) grain varieties grown in Kenya. Food Nutr Bull 23:241-245.

Mann JA, Kimber CT, Miller FR (1983) The origin and early cultivation of Sorghums in Africa. Bulletin No. 1454, Texas Agricultural Experimental Station: College Station, TX, USA.

Maunder A, Sharp G (1963) Localization of outcrosses within panicle of fertile sorghum. Crop Sci 3:449.

McWhorter CG (1971) Growth and development of Johnsongrass ecotypes. Weed Sci 19:141-147.

Mehra SP, Bhatia RK and Kanwar RS (1994) Chemical control of Johnson grass (Sorghum halepense L.) in sugarcane. Journal of Research, Punjab Agricultural University 31:131-137.

Menkir A, Golsbrough P, Ejeta G (1997) RAPD-based assessment of genetic diversity in cultivated races of sorghum. Crop Sci 37:564-569.

Menz MA, Klein RR, Unruh NC, Rooney WL, Klein PE, Mullet JE (2004) Genetic diversity of public inbreds of sorghum determined by mapped AFLP and SSR markers. Crop Sci 44:1236-1244.

Mohan SM, Madhusudhana R, Mathur K, Howarth CJ, Srinivas G, Satish K, Reddy RN, Seetharama N (2009) Co-localization of quantitative trait loci for foliar disease resistance in sorghum. Plant Breed 128:532-535.

Moriya A (1940) Contributions to the cytology of genus Saccharum I. Observations on the F1 progeny of sugar cane-sorghum hybrids. Cytologia 11:117-135.

Morrell PL, William-Coplin TD, Lattu AL, Bowers JE, Chandler JM, Paterson AH (2005) Crop-to-weed introgression has impacted allelic composition of Johnsongrass populations with and without recent exposure to cultivated sorghum. Mol Ecol 14:2143-2154.

Mott JJ (1978) Dormancy and germination in five native grass species from savannah woodland communities of the Northern Territory. Aust J Bot 26: 621-631.

Murray SC, Rooney WL, Mitchell SE, Sharma A, Klein PE, Mullet JE, Kresovich S (2008b) Genetic improvement of sorghum as a biofuel feedstock: II. QTL for stem and leaf structural carbohydrates. Crop Sci 48:2180-2193.

Murray SC, Sharma A, Rooney WL, Klein PE, Mullet JE, Mitchell SE, Kresovich S (2008a) Genetic improvement of sorghum as a biofuel feedstock: I. QTL for stem sugar and grain nonstructural carbohydrates. Crop Sci 48:2165-2179.

Murty BR, Arunachalam V, Saxena MBL (1967) Cataloguing and classifying a world collection of genetic stocks of sorghum. Ind J Genet 27:1-312.

Murty DS, Tabo R, Ajayi O (1994) Sorghum hybrid seed production and management. Information Bulletin No. 41. International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India.

Mustalahti K, Lohiniemi S, Collin P, Vuolteenaho N, Laippala P, Maki M (2002) Gluten-Free Diet and Quality of Life in Patients with Screen-Detected. Eff Clin Pract 5:105-113.

Nagaraj N, Reese JC, Tuinstra MR, Smith CM, Amand PS, Kirkham MB, Kofoid KD, Campbell LR, Wilde GE (2005) Molecular mapping of sorghum genes expressing tolerance to damage by greenbug (Homoptera: Aphididae). J Econ Entomol 98:595-602.

Nagy ED, Lee TC, Ramakrishna W, Xu ZJ, Klein PE, SanMiguel P, Cheng CP, Li JL, Devos KM, Schertz K, Dunkle L, Bennetzen JL (2007) Fine mapping of the Pc locus of *Sorghum bicolor*, a gene controlling the reaction to a fungal pathogen and its host selective toxin. Theor Appl Genet 114:961-970.

Nair NV (1999) Production and cyto-morphological analysis of intergeneric hybrids of Sorghum x Saccharum. Euphytica 108:187-191.

Nair NV, Selvi A, Sreenivasan TV, Pushpalatha KV, Sheji Mary (2006) Characterization of intergeneric hybrids of Saccharum using molecular markers. Genetic Resour Crop Evol 53:163-169.

Nelson JC, Wang S, Wu Y, Li X, Antony G, White FF, Yu J (2011) Single nucleotide polymorphism discovery by high-throughput sequencing in sorghum. BMC Genomics 12:1-15.

Nguyen TV, Tran TT, Martine C, Geert A (2007) Agrobacterium-mediated transformation of sorghum (*Sorghum bicolor* (L.) Moench) using an improved in vitro regeneration system. Plant Cell Tiss Organ Cult 91:155-164.

Nikkhah A, M Alikhani, H Amanlou (2004). Evaluation of Feeding Ground or Steam-flaked Broom Sorghum and Ground Barley on Performance of Dairy Cows in Midlactation. J Dairy Sci 87:122-130.

Oliver AL, Grant RJ, Pedersen JF, O'Rear J (2004). Comparison of Brown Midrib-6 and -18 Forage Sorghum with Conventional Sorghum and Corn Silage in Diets of Lactating Dairy Cows. J. Dairy Sci 87:637-644.

Ou-Lee T, Turgeon R, Wu R (1986) Expression of a foreign gene linked to either a plant-virus or a Drosophila promoter, after electroporation of protoplasts of rice, wheat, and sorghum. Proc Natl Acad Sci USA 83:6815-6819.

Parh D (2005) DNA-based markers for ergot resistance in sorghum. PhD thesis. University of Queensland, Brisbane.

Parh DK, Jordan DR, Aitken EAB, Mace ES, Jun-ai P, McIntyre CL, Godwin ID (2008) QTL analysis of ergot resistance in sorghum. Theor Appl Genet 117:369-382.

Park JG, Lee SH, Chung IM, Park Y (2012) Sorghum extract exerts an anti-diabetic effect by improving insulin sensitivity via PPAR-γin mice fed a high-fat diet. Nutr Res Pract 6:322-327.

Parodi LR (1943) Una neuva especie de sorghum cultivada en las Argentina. Rev. Argentina de Agron. 10:361-372.

Patel ZG, Raj VC, Patel HC, Patel CL (1993) Integrated weed management in pigeonpea (Cajanus cajan (L.) Millsp.). Integrated weed management for sustainable agriculture. Proceedings of an Indian Society of Weed Science International Symposium, Hisar, India, 18-20 November 1993 Vol. III pp:152-153.

Paterson AH, Bowers JE, Bruggmann R, Dubchak I, Grimwood J, Gundlach H, Haberer G, Hellsten U, Mitros T, Poliakov A, Schmutz J, Spannagl M, Tang HB, Wang XY, Wicker T, Bharti AK, Chapman J, Feltus FA, Gowik U, Grigoriev IV, Lyons E, Maher CA, Martis M, Narechania A, Otillar RP, Penning BW, Salamov AA, Wang Y, Zhang LF, Carpita NC, Freeling M, Gingle AR, Hash CT, Keller B, Klein P, Kresovich S, McCann MC, Ming R, Peterson DG, Mehboobur R, Ware D, Westhoff P, Mayer KFX, Messing J, Rokhsar DS (2009) The *Sorghum bicolor* genome and the diversification of grasses. Nature 457:551-556.

Paterson AH, Lin YR, Li Z, Schertz KF, Doebley JF, Pinson SRM, Liu SC, Stansel JW, Irvine JE (1995a) Convergent domestication of cereal crops by independent mutations at corresponding genetic loci. Science 269:1714-1718.

Paterson AH, Schertz KF, Lin Y-R, Liu SC, Chang YL (1995b) The weediness of wild plants: molecular analysis of genes influencing dispersal and persistence of Johnsongrass, Sorghum halepense (L.) Pers. Proc Natl Acad Sci USA 92:6127-6131.

Pawar SS (2002) Sensitivity to Sorghum Vulgare (Jowar) Pollens in Allergic Bronchial Asthma and Effect of Allergen Specific Immunotherapy. Indian J Allergy Asthma Immunol. 16:41-45.

Pedersen JF, Toy JJ and Johnson B (1998) Natural outcrossing of sorghum and sudangrass in the central great plains. Crop Sci 38:937-939.

Pereira MG, Lee M (1995) Identification of genomic regions affecting plant height in sorghum and maize. Theor Appl Genet 90:380-388.

Pereira MG, Ahnert D, Lee M, Klier K (1995) Genetic-mapping of Quantitative Trait Loci for panicle characteristics and seed weight in sorghum. Braz J Genet 18:249-257.

Perumal R, Menz MA, Mehta PJ, Katile S, Gutierrez-Rojas LA, Klein RR, Klein PE, Prom LK, Schlueter JA, Rooney WL, Magill CW (2009) Molecular mapping of Cg1, a gene for resistance to anthracnose (Colletotrichum sublineolum) in sorghum. Euphytica 165:597-606.

Peterson DG, Schulze SR, Sciara EB, Lee SA, Bowers JE (2002) Integration of Cot analysis, DNA cloning, and high-throughput sequencing facilitates genome characterization and gene discovery. Genome Res 12:795-807.

Pontieri P, Mamone G, De Caro S, Tuinstra MR, Roemer E, Okot J, De Vita P, Ficco DB, Alifano P, Pignone D, Massardo DR and Del Giudice L (2013). Sorghum, a healthy and gluten-free food for celiac patients as demonstrated by genome, biochemical, and immunochemical analyses. J. Agric. Food Chem. 61:2565-2571.

Price HJ, Dillon SL, Hodnett G, Rooney W, Ross L, Johnston JS (2005) Genome Evolution in the genus Sorghum (Poaceae). Ann Bot 95:219-227.

Price HJ, GL Hodnett, BL Burson, SL Dillon, DM Stelly, WL Rooney (2006) Genotype-dependent interspecific hybridization of *Sorghum bicolor*. Crop Sci 46:2617-2622.

Putnam AR, DeFrank J (1983) Use of phytotoxic plant residues for selective weed control. In: Proc. Br. Crop Prot Conf Weeds 2:173-181.

Rakshit S, Gomashe SS, Ganapathy KN, Elangovan M, Ratnavathi CV, Seetharama N, Patil JV (2012) Morphological and molecular diversity reveal wide variability among sorghum Maldandi landraces from south India. J Plant Biochem Biotechnol 21:145-156.

Rami JF, Dufour P, Trouche G, Fliedel G, Mestres C, Davrieux F, Blanchard P, Hamon P (1998) Quantitative trait loci for grain quality, productivity, morphological and agronomical traits in sorghum (*Sorghum bicolor* (L.) Moench). Theor Appl Genet 97:605-616.

Ramu P, Billot C, Rami JF, Senthilvel S, Upadhyaya HD, Ananda Reddy L, Hash CT (2013) Assessment of genetic diversity in the sorghum reference set using EST-SSR markers. Theor Appl Genet 111:399-409.

Rao SS, Seetharama N, Kiran Kumar KA, Vanderlip RL (2004) Characterization of Sorghum Growth Stages. NRCS Bulletin Series no.14. National Research Centre for Sorghum, Rajendranagar, Hyderabad 500 030, Andhra Pradesh, India.

Reddy BVS, Kumar AA, Reddy PS, Elangovan M (2008) Sorghum germplasm: diversity and utilization. In: Sorghum genetic enhancement: research process, dissemination and impacts. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Andhra Pradesh, India pp:153-169.

Reddy BVS, Ramesh S, Sanjana Reddy P, Ramaiah B, Salimath PM, Rajashekar K (2005) Sweet sorghum–A potential alternative raw material for bioethanol and bio-energy. Intl Sorghum Millets Newsl 46:79-86.

Rice EL (1984) Allelopathy, 2nd edition. Academic Press, Orlando, FL, USA.

Ritter KB, Jordan DR, Chapman SC, Godwin ID, Mace ES, McIntyre CL (2008) Identification of QTL for sugar-related traits in a sweet x grain sorghum (*Sorghum bicolor* (L.) Moench) recombinant inbred population. Mol Breed 22:367-384.

Rooney LW, Miller FR (1982) In: Proceedings of the International Symposium on Sorghum Grain Quality. (JV Mertin, Eds.). ICRISAT, Patancheru, AP, India pp:143-162.

Rooney LW, Serna-Saldivar SO (2000) Chapter 5 Sorghum. In: Handbook of Cereal Science and Technology, Second Edition, Eds. K. Kulp and J. G. Ponts, Jr. Marcel Dekker, Inc. New York, NY pp:149-176.

Sagnard F, Deu M, Dembele D, Leblois R, Toure L, Diakite M, Calatayud C, Vaksma M (2011) Genetic diversity, structure, gene flow and evolutionary relationships within the *Sorghum bicolor* wild-weedy-crop complex in a western African region. Theor Appl Genet 123:1231-1246.

Salas Fernandez MG, Hamblin MT, Li L, Rooney WL, Tuinstra MP, Kresovich S (2008) Quantitative trait loci analysis of endosperm color and carotenoid content in sorghum grain. Crop Sci 48:1732-1743.

Sanchez RL, Smeltzer DG (1965) Sorghum pollen viability. Crop Sci 5(2):111-113.

Satish K, Srinivas G, Madhusudhana R, Padmaja PG, Nagaraj Reddy R, Murali Mohan S, Seetharama N (2009) Identification of quantitative trait loci (QTL) for resistance to shoot fly in sorghum [*Sorghum bicolor* (L.) Moench]. Theor Appl Genet 119:1425-1439.

Schertz KF, Dalton LG (1980) Sorghum. In: Fehr W and Hadley HH (eds.) Hybridization of crop plants. American Society of Agronomy: Madison, WI, USA pp:577-588.

Schmidt MR, Bothma GC (2005) Indications of bee pollination in Sorghum and its implications in transgenic biosafety. Int Sorghum Millet Newsl 46:72-75.

Seetharama N (1977) Variability in Sorghum growth stages. Presented at the International Sorghum Workshop, 6-12 May 1977. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India.

Sharma RK, Sachan SN (1994) New hosts of rust fungi from Himachal Pradesh. Adv Plant Sci 7:154-158.

Shiringani AL, Frisch M, Friedt W (2010) Genetic mapping of QTLs for sugar-related traits in a RIL population of *Sorghum bicolor* L. Moench. Theor Appl Genet 121:323-336.

Shridhar J, Bhat RS, Sumangala B, Kuruvinashetti MS (2010) Agrobacterium-mediated transformation studies in sorghum using an improved gfp reporter gene. J SAT Agri Res 8.

Simpson GM (2007) Seed Dormancy in Grasses. Cambridge University Press.

Snowden JD (1936) The cultivated races of Sorghirnz, Adlard & Son, London.

Sridhara S, Kumar L, Verma J, Arora N, Gaur SN, Singh BP (2002) Immunobiochemical characterization of Sorghum vulgare pollen allergens prevalent in tropical countries. Ind J Allergy Asthma Immunol 16:33-39.

Srinivas G, Satish K, Madhusudhana R, Nagaraja Reddy R, Murali Mohan S, Seetharama N (2009) Identification of quantitative trait loci for agronomically important traits and their association with genic-microsatellite markers in sorghum. Theor Appl Genet 118:1439-1454.

Srinivasa Reddy P, Fakrudin B, Rajkumar, Punnuri SM, Arun SS, Kuruvinashetti MS, Das IK, Seetharama N (2008) Molecular mapping of genomic regions harboring QTLs for stalk rot resistance in sorghum. Euphytica 159:191-198.

Stephens JC, Quinby JR (1934) Anthesis, pollination, and fertilization in sorghum. J Agric Res 49:123-136.

Stephens JG, Holland RF (1954) Cytoplasmic male sterility for hybrid sorghum seed production. Agron J 46:20-23.

Subramaniam V, Jambunathan R (1980) Traditional methods of processing Sorghum (*Sorghum bicolor*) and Pearl millet (Pennisetum americanum) grains in India. Rep. Int Assoc Cereal Chem 10:115-188.

Subudhi PK, Rosenow DT, Nguyen HT (2000) Quantitative trait loci for the stay green trait in sorghum (*Sorghum bicolor* L. Moench): Consistency across genetic backgrounds and environments. Theor Appl Genet 101:733-741.

Sukumaran S, Xiang W, Bean SR, Pederson JF, Kresovich S, Tuinstra MR, Tesso TT, Hamblin MT, Yu J (2012) Association mapping for grain quality in a diverse sorghum collection. Plant Genome 5:126-135.

Tadesse Y, Sagi L, Swennen R, Jacobs M (2003) Optimization of transformation conditions and production of transgenic sorghum (*Sorghum bicolor*) via microparticle bombardment. Plant Cell Tissue Organ Cult 75:1-18.

Tao KLJ (1982) Improving the germination of Johnsongrass (Sorghum halepense) seeds with acid scarification. J. Seed Technol. East Lansing: Assoc Off Seed Analyst 7:1-9.

Tao YZ, Hardy A, Drenth J, Henzell RG, Franzmann BA, Jordan DR, Butler DG, McIntyre CL (2003) Identifications of two different mechanisms for sorghum midge resistance through QTL mapping. Theor Appl Genet 107:116-122.

Tao YZ, Henzell RG, Jordan DR, Butler DG, Kelly AM, McIntyre CL (2000) Identification of genomic regions associated with stay green in sorghum by testing RILs in multiple environments. Theor Appl Genet 100:1225-1232.

Tao YZ, Jordan DR, Henzell RG, McIntyre CL (1998) Identification of genomic regions for rust resistance in sorghum. Euphytica 103:287-292.

Taramino G, Tarchini R, Ferrario S, Lee M, Pe'ME (1997) Characterisation and mapping of simple sequence repeats (SSRs) in *Sorghum bicolor*. Theor Appl Genet 95:66-72.

Taylora JRN, Schoberb TJ, Beanb SR (2006) Novel food and non-food uses for sorghum and millets. J Cereal Sci 44:252-271.

Teetes GL, Seshu Reddy KV, Leuschner K, House LR (1983) Sorghum insect identification handbook. Information Bulletin No. 12. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad 500 016, A.P., India in collaboration with the Texas Agricultural Experiment Station, Texas A & M University, College Station , Texas, USA.

Tejinder KM, Dweikat I, Sato SJ, Neresian N, Xu K, Ge Z, Wang D, Elthon T, Clemente T (2011) Expression of the rice CDPK-7 in sorghum: molecular and phenotypic analyses. Plant Mol Biol 75:467-479.

Tester WC, McCormick G (1954) Germination of Johnsongrass: results of tests made by the Arkansas State Plant Board. Proceedings Assoc Off Seed Analyst 44:96-99.

Tuinstra MR, Wedel J (2000) Estimation of pollen viability in grain sorghum. Crop Sci 40:968-970.

Tuinstra MR, Grote EM, Goldsbrough PB, Ejeta G (1997) Genetic analysis of post-flowering drought tolerance and components of grain development in *Sorghum bicolor* (L.) Moench. Mol Breed 3:439-448.

Van Rensburg SJ (1981) Epidemiologic and Dietary Evidence for a Specific Nutritional Predisposition to Esophageal Cancer. J Natl Cancer Inst 67:243-251.

Vanderlip RL, Reeves HE (1972) Growth stages of sorghum. Agron J 64:13-16.

Vavilov NI (1951) The origin, variation, immunity and breeding of cultivated plants. Chron Bot 13:1-366.

Venkataraman RBTS, Thomas R (1932) Sugarcane-sorghum hybrids. Part I. General outline and early characters. Ind J Agri Sci 2:19-27.

Visarada KBRS, Padmaja PG, Saikishore N, Pashupatinath E, Royer M, Seetharama N, Patil JV (2014) Production and evaluation of transgenic sorghum for resistance to stem borer. In Vitro Cell Dev Biol Plant 50:176-189.

Wang D, Bean S, McLaren J, Seib P, Madl R, Tuinstra M, Shi Y, Lens M, Wu X, Zhao R (2008) Grain Sorghum is a Viable Feedstock for Ethanol Production. J Ind Microbiol Biotechnol 35:313-320.

Warwick SI, Black LD (1983) The biology of Canadian weeds. Can J Plant Sci 63:997-1014.

Warwick SI, Phillips D, Andrews C (1986) Rhizome depth: The critical factor in winter survival of Sorghum halepense (L.) Pers. (Johnsongrass). Weed Res 26:381-388.

Wendorf F, AE close, R Schild, K Wasylikowa, RA Housley, JR Harlan, H Krolik (1992) Saharan exploitation of plants 8,000 years bp. Nature 359:721-724.

Wiersema JH, Dahlberg J (2007) The nomenclature of *Sorghum bicolor* (L.) Moench (Gramineae). Taxon 56:941-946.

Williams RJ, Frederiksen RA, Girard JC (1978) Sorghum and Pearl millet disease identification hand book. Information Bulletin No. 2. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad 500 016, A.P, India in collaboration with the Texas Agricultural Experiment Station, Texas A & M University, College Station , Texas, USA.

Winn J, Mason R, Robbina A, Rooney W, Hays D (2009) QTL mapping of a high protein digestibility trait in *Sorghum bicolor*. Int J Plant Genom doi:10.1155/2009/471853.

Wu YQ, Huang Y (2006) An SSR genetic map of *Sorghum bicolor* (L.) Moench and its comparision to a published genetic map. Genome 50:84-89.

Wu YQ, Huang YH (2008) Molecular mapping of QTLs for resistance to the greenbug Schizaphis graminum (Rondani) in *Sorghum bicolor* (Moench). Theor Appl Genet 117:117-124.

Wu YQ, Huang YH, Porter DR, Tauer CG, Hollaway L (2007) Identification of a major quantitative trait locus conditioning resistance to greenbug Biotype E in sorghum PI550610 using simple sequence repeat markers. J Econ Entomol 100:1672-1678.

Xu WW, Subudhi PK, Crasta OR, Rosenow DT, Mullet JE, Nguyen HT (2000) Molecular mapping of QTLs conferring stay-green in grain sorghum (*Sorghum bicolor* L. Moench). Genome 43:461-469.

Yang L, Browning JD, Awika JM (2009) Sorghum 3-deoxyanthocyanins possess strong phase II enzyme inducer activity and cancer cell growth inhibition properties. J Agric Food Chem 57:1797-1804.

Zhang M, Tang Q, Chen Z, Liu J, Cui H, Shu Q, Xia Y, Altosaar I (2009) Genetic transformation of Bt gene into sorghum [*Sorghum bicolor* (L.)] mediated by Agrobacterium tumefaciens. Chin J Biotech 25:418-423.

Zhao R, SR Bean, BP Ioerger, D Wang, DL Boyle (2008) Impact of Mashing on Sorghum Proteins and its Relationship to Ethanol Fermentation. J Agric Food Chem 56:946-953.

Zhao Z, Cai T, Tagliani L, Miller M, Wang N, Pang H, Rudert M, Schroeder S, Hondred D, Seltzer J, Pierce D (2000) Agrobacterium-mediated sorghum transformation. Plant Mol Biol 44:789-798.

Zheng LY, Guo XS, He B, Sun LJ, Peng Y, Dong SS, Liu TF, Jiang S, Ramachandran R, Liu CM, Jing HC (2011) Genome-wide patterns of genetic variation in sweet and grain sorghum (*Sorghum bicolor*). Genome Biol 12: R114.

Zhu H, Muthukrishnan S, Krishnaveni S, Wilde G, Jeoung JM, Liang GH (1998) Biolistic transformation of sorghum using a rice chitinase gene. J Genet Breed 52:243-252.

Important Contacts: **NATIONAL PROJECT DIRECTOR**
Shri Hem Kumar Pande, Special Secretary

NATIONAL PROJECT COORDINATOR
Dr. Ranjini Warrier, Advisor

Ministry of Environment, Forest and Climate Change
Indira Paryavaran Bhawan, Ali Ganj, Jor Bagh Road, New Delhi - 110003

In association with

Indian Institute of Millets Research
Rajendranagar, Hyderabad -500 030

For further information, please contact at E-mail: biosafety-mef@nic.in