SORGHUM

Innovative Technologies for Cultivation and Valorization

FULL ENGLISH TRANSLATION

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TRANSLATOR'S NOTE

This English translation covers the full 425-page Romanian scientific monograph on sorghum cultivation and valorization technologies. The original text is an OCR-extracted and expert-translated rendition from scanned PDFs. Scientific terminology, Romanian names, and institution names have been preserved in their standard English forms. Some OCR artifacts in the original scanned documents may have introduced minor imperfections; these have been corrected where context was clear.

SCOPE: This translation covers Volumes 1–4 (pages 1–426), including all 10 chapters: Origin & History; Systematics & Distribution; Genetics & Breeding; Morphology; Chemical Composition; Importance of the Species; Ecological Requirements; Cultivation Technology (8 sub-chapters); Diseases & Pests; and Valorization of Sweet Sorghum (11 sub-chapters).

SORGHUM — INNOVATIVE TECHNOLOGIES FOR CULTIVATION AND VALORIZATION

[Sorgul — Tehnologii inovative de cultivare si valorificare]

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FOREWORD

Sorghum is widely cultivated on all continents, in tropical and temperate zones. Slightly over 40% of its production is intended for human food, mainly in Africa and Asia, where it is consumed as whole grain, rice substitute, grits, flour (gluten-free), or after transformation as sugar, or after the addition of malt and fermentation, as alcohol (beer, spirits, etc.).

The largest share of sorghum production is used in animal husbandry and industry. In recent years, increasing emphasis has been placed on the high capacity of sweet sorghum to produce biomass for reducing dependence on fossil fuels and for producing biofuels and clean, non-polluting green energy.

The promotion of sorghum and the development of its hybrid genetics for diverse uses — grain sorghum for human and animal consumption; forage sorghum; sweet sorghum as an energy crop or for non-food segments — constitute unanimously shared objectives of sorghum growers. To respond to this goal, a European interprofessional sorghum organization was created. Its founding assembly took place in Brussels on September 26, 2017, thus forming the organization Sorghum ID (meaning "sorghum — international development").

In an effort to reduce carbon emissions, the European Commission has set an immediate mandatory objective requiring that one-fifth of energy produced at EU level come from renewable sources, with energy crops being one of the key pathways for achieving this target.

European-level policies envisage clear coordination between energy crops and food crops, so that each country can determine the most appropriate land use to gain dual benefits — in both food production and energy production — in a sustainable manner.

In mid-2016, at the initiative of the French interprofessional federation for maize and sorghum seed production (F.N.P.S.M.S.), two projects were submitted targeting the promotion of sorghum and its genetics in Europe. These projects were submitted to Brussels bodies for European funding.

These two promotion programs — backed by national budgets for a three-year period — enabled the promotion of grain sorghum and forage sorghum, as well as the genetics of newly created hybrids, in five EU member states: France – Italy – Spain – Romania – Bulgaria, and in two non-EU Eastern European countries: Russia and Ukraine.

The actions undertaken within these two programs were of several types: communication and promotional materials, demonstration plots, conferences, technical publications, agricultural fairs, study visits and journalist tours, websites, video clips, etc. All these actions led to better public awareness of sorghum cultivation, highlighted the advantages of this crop and contributed to the expansion of cultivated areas.

Expanding sorghum cultivation in Romania represents more than a realistic prospect — it is a necessity, given the agronomic advantages of growing this crop, and the fact that sorghum can considerably influence the future of agriculture, the chemical industry, the energy sector and the food industry.

Romania has integrated into the economic system of the European Union for ensuring food self-sufficiency, and for this reason it is necessary to develop and apply new technologies for the cultivation and integral, integrated valorization of sorghum grain and biomass production, as well as the residues and by-products resulting from processing.

In our country, a large share of agricultural land could be used for energy crops without requiring special land preparation. After minimal processing, the energy resulting from the valorization of produced biomass (thermal energy, biofuels, biogas) can be gradually introduced into the existing energy distribution system.

THE AUTHORS

INTRODUCTION

Sorghum is the world's fifth most important bread cereal, with impressive genetic diversity and multiple end uses. Globally, it is primarily used in animal feed, while its uses in human nutrition are justified by its high content of vitamins and antioxidants, good digestibility and the absence of gluten. All of this is complemented by the valorization of plant biomass for the production of ethanol, biogas, biomaterials, etc.

Due to its universally acknowledged drought tolerance, short growing season and relatively low production costs, farmer interest in sorghum cultivation is growing, a trend observed both worldwide and in Romania. The ability of sorghum to adapt to water deficits is well established (85% of arable land in Europe lacks irrigation systems), and in most cases crop production does not require irrigation.

The high tolerance to biotic and abiotic stress factors, the physiological mechanisms by which the sorghum plant conserves and efficiently uses water, the variety of genotypes developed over the past 10–15 years with superior capacity to exploit local climatic conditions and with greatly increased yields — both quantitatively and qualitatively — make this crop an agronomic alternative that will play an essential role in ensuring biodiversity in agro-ecosystems and an important source of income in the economy of the future.

Sorghum's many favorable traits have led to its spread in cultivation predominantly in developing countries, mainly in Africa and Asia, where more than 90% of the world's sorghum-cultivated area is found.

In terms of production volumes, the USA currently leads with an annual production of approximately 9 million tonnes, followed by Nigeria (6.9 MMT), Ethiopia (5.0 MMT), Mexico (5.0 MMT), India (4.5 MMT), and China (3.6 MMT).

The trend in the European Union over the past decade has been to stimulate the expansion of sorghum-cultivated areas, taking into account the real advantages of this crop, and because farmers — most severely affected by climate change and reduced rainfall during the vegetative period of maize — are seeking a viable alternative that provides consistent and reliable yields for the livestock sector.

Expanding this crop in Europe, and implicitly in Romania, would therefore allow for reduced dependence on imports for protein supply and even export opportunities to meet global demand, while simultaneously developing local markets.

Sorghum hybrids obtained through the EU breeding process comply with the EU's general policy on genetically modified organisms (GMOs) and do not contain biotechnology-induced traits — an important factor for certain global markets, which increases the suitability of this species for use in organically certified farms and holdings.

According to the Sorghum ID Professional Association, the 8 pillars of European selection for sorghum are:

- Yield and stability
- Precocity combined with tolerance to low temperatures during germination and flowering
- Drought tolerance
- Disease resistance
- Pest resistance
- Production quality: very low tannin content, seed color and texture, starch content, sanitary quality of grain, etc.
- Presence of the "stay green" trait
- Fodder quality: digestibility and nutritional value, carbohydrate content, etc.

Climate change in Romania, with an increasingly evident impact on the productive capacity of crops and especially on the safety and consistency of yields, combined with the absence of irrigation systems for most agricultural land, has brought sorghum back to the attention of many farmers as a viable alternative to maize.

New sorghum genotypes created and marketed globally require mandatory steps for testing their productive potential and optimizing cultivation technologies, correlated with the most modern technologies for the integral valorization of production, by-products and residues from grain and sweet sorghum crops, applicable to the livestock, energy and food sectors.

Taking into account the arguments presented above, within the research programme of Complex Project No. 9/PCCDI/2018 "Complex System for the Integral Valorization of Agricultural Species with Energy and Food Potential," an extensive study was carried out on sorghum cultivation technology in different regions of Romania: Central Moldova, the Oltenia Plain, and the sandy zone of Oltenia. Experiments were conducted at the Agricultural Research and Development Station Secuieni (Moldova) on a cambic phaeozem, at the Agricultural Research and Development Station Caracal (Oltenia Plain) on an argic chernozem, and at the Research and Development Station for Plant Culture on Sandy Soils Dabuleni on sandy soil. The results obtained formed the basis for recommendations on optimizing the main technological sequences for achieving high, economically efficient yields while maintaining environmental purity and ecological balance.

The study was complemented by elements concerning the integral valorization of grain and biomass production, developed by the National Research and Development Institute for Machines and Installations for Agriculture and Food Industry (INMA Bucharest), the National Research and Development Institute for Pedology, Agrochemistry and Environmental Protection (ICPA Bucharest), the National Research and Development Institute for Food Bioresources (IBA Bucharest), and the "Dunarea de Jos" University of Galati.

CHAPTER I

ORIGIN AND HISTORY OF THE SPECIES

1.1. ORIGIN OF SORGHUM

Cultivated sorghum belongs to the family Poaceae (Gramineae), genus Sorghum, species Sorghum bicolor (L.) Moench. Researchers who have studied this species have concluded that: "There is no other crop of major importance that varies as much as sorghum."

The center of origin of sorghum has been debated since ancient times and has not yet been precisely established. According to some authors, sorghum originated in India, while others place its origin in Equatorial Africa. However, most studies point to the northeastern part of Africa — specifically the regions of Ethiopia and Sudan — where sorghum cultivation began 4,000–3,000 years BCE (Dillon et al., 2007b) and where hundreds of distinct genotypes exist. The greatest richness of primitive forms is found in Ethiopia and in East Africa, West Africa, India, China, and the Arabian Peninsula, which serve as secondary centers of sorghum diversification into new species.

According to Bilteanu et al. (1991), most forms of cultivated sorghum originate from the Abyssinian gene center, while the variety kaoliang originates from the Chinese center.

Cultivated sorghum is Sorghum bicolor subsp. arundinaceum (Doggett, 1988). The species Sorghum bicolor (L.) Moench includes all cultivated sorghum varieties, as well as a group of semi-wild plants largely associated with weeds. The degree of morphological variation in S. bicolor is so great that Snowden (1936, 1955) divided this species into 28 cultivated forms and 24 related wild forms.

The species was domesticated early through a selection process in which advantageous traits for cultivation were pursued (Doggett, 1988). In addition to selection, geographic isolation and recombination led to the creation of a large number of types, varieties and races of sorghum. Through these processes, three groups of Sorghum bicolor were obtained: cultivated, wild and intermediate (Kimber, 2000). Cultivated varieties were improved morphologically (plant height and inflorescence characteristics) and qualitatively, for use in human and animal nutrition, for fiber and as construction material (Dillon et al., 2007b).

According to older literature, three domestication centers for sorghum in Africa still persist today.

1.2. HISTORY OF THE SPECIES

The oldest inscription about sorghum was found during an archaeological excavation at Nabta Playa, near the Egyptian-Sudanese border, dated to 8,000 years BCE.

It is assumed that sorghum was introduced into cultivation approximately 7,000 years ago in Equatorial Africa, while evidence shows that the species has been cultivated in India for 4,500 years. In the Neolithic period, sorghum spread to Tanzania, Kenya, Uganda and Congo (Cole, 1963), then southward across Africa in the first century CE, and eastward into Asia and Australia.

Although it is difficult to determine exactly when sorghum spread to different regions, it is certain that this spread occurred from northeastern Africa to other parts of Africa (1500–1000 BCE) through trade. It is presumed that sorghum was subsequently spread from Africa to the Middle East, the Far East and India (900–700 BCE) by sea and trade routes.

The genus Sorghum spread almost continuously from southern Africa to the subtropical zone of Australia, where it arrived with European colonization.

Today, in cultivation, there exists a wide range of varieties and hybrids, derived mainly from Africa and India, originating from bicolor sorghum with the varieties:

- cafra — widespread in central and eastern Africa
- shallu — widespread in India and West Africa
- kaoliang — cultivated in China
- feterita — cultivated in Sudan

- hegari — present in Sudan
- durra — cultivated in Central and East Africa
- milo — cultivated in Central and East Africa

The origin and domestication history of broom sorghum remains uncertain. There is no information attesting that it originated from the same centers as cultivated sorghum (Weibel, 1970). On the contrary, information about it has been found outside Africa, where it was first cultivated and used in America and Europe, preceding all other types of sorghum cultivated in Africa (Doggett, 1988; Franklin, 1757). Wild forms of sorghum resembling broom sorghum were found in Korea and Japan (Ball, 1910), where, according to Snowden (1936), Bullock collected broom sorghum panicles from Kiukiang, China and Veitch, Japan. Doggett (1988) reported the existence of cultivated broom sorghum varieties in India.

There is evidence of sorghum's presence in India from the 1st century CE and in China from the 3rd century CE. There is no doubt that numerous varieties existed there from the beginning of the Christian era, but no classification or description was carried out until later.

In China, the earliest documented writings about sorghum (broom sorghum) appear from the 3rd century in the Journal of Natural Sciences from Zhanghua, though it is not known with certainty whether the "broom millet from Sichuan" described in this manuscript is definitively sorghum. What is clear is that Zhen Wang (1313) described broom sorghum as follows: "Its stem is over 3.3 m tall with an ear as large as a broom and its seeds black as tuna" (Qingshan and Dahlberg, 2001). In this country, cultivated sorghum easily adapted to temperate conditions, and as a result, many varieties were developed under the name Kaoliang (Doggett, 1988).

In Egypt, sorghum was considered one of the earliest plants domesticated by humans for food or animal feed. Ball (1910) drew attention to a statement by Woenig — that a sorghum field was painted on the walls of the tomb of Amenemhet, constructed at least 2,200 years BCE. However, there is considerable doubt that the painted crop actually represents sorghum, because Newberry (1893) reproduces this painting and shows reapers harvesting a crop that, due to the lack of detail, could be confused with flax or other cereals. Piedallu (1923) extensively discussed whether the scene on the walls of Amenemhat's tomb at Beni Hasan depicts sorghum and concluded that it actually illustrates the harvesting of flax, and that there is no evidence that the ancient Egyptians knew of sorghum. Piedallu's logic appears sound, as many scientists agree, because the people depicted are engaged in pulling plants — a harvesting method more typical of flax than sorghum. Piedallu also noted that sorghum grain was commonly used as food for the poorest people, which would not explain its presence in the tombs of kings who used wheat for bread. Nevertheless, a relief taken from the palace of Sennacherib at Nineveh, currently held at the British Museum in London, presents a precise image of a sorghum field, indicating that sorghum was cultivated there as early as 700 BCE.

In the United States, the earliest writings on the importance and uses of sorghum date from 1757, when Benjamin Franklin publicized the use of sorghum in broom production. Cultivated sorghum first arrived in America at the end of the 1800s, through the slave trade (Doggett 1988; FAO 1995).

Sorsby (1855) claimed to have seen sorghum cultivated in Georgia in 1838, mentioning two varieties — "White" sorghum and "Brown-red" sorghum — his work being devoted more to the uses of sorghum than to its biology and agronomy.

Browne (1855) mentioned that among "seeds and planting material recently introduced into the United States" there was a variety of "hard sorghum" received at St. Martin (North America) from the West Indies, and a variety of "sweet sorghum" sent from China to France and subsequently to America. He later provided details about sweet sorghum varieties, referring to varieties collected by Leonard Wray from Natal, South Africa. Olcott, in 1857, published a description of sorghum varieties imported from South Africa by Leonard Wray.

Hedges (1863) presented information on 15 sorghum varieties brought to America from South Africa by Leonard Wray. He also provided information on the introduction to America of a Chinese sorghum variety that obtained a US patent in November 1854. This variety was obtained at Vilmorin, Andrieux & Co., Paris, France, in 1851, having been sent to France by the Count of Montigny, then consul in Shanghai, China.

Pech (1866) presented the botanical history of sorghum and created a classification scheme with illustrations of panicles from seven sorghum varieties. In this scheme, sorghum was divided into two groups: the Liberian group, which included six of Wray's varieties (Ekothla, Koombana, Boomowana, Eengha, Booeana and Eednomoodon), and a second group that included: Black Imphee, Red Imphee (Shlagoova) and White Imphee. This classification was not approved by botanists because, according to Wray's descriptions, there were large differences among the six African varieties, making it incorrect to include them in the same group. A series of classifications by American botanists followed, but none was fully approved.

Shaw (1900) divided sorghum into two main classes: sweet sorghum and non-sweet sorghum, stating: "This classification is based on the presence of sugar in considerable quantities at maturity in some cultivars, or its absence in others."

Denton (1907) published the first bulletin for farmers presenting the results obtained by the Department of Agriculture at Medicine Lodge, Kansas, regarding syrup production from sorghum. A series of studies followed that established the value of sweet sorghum.

Martin and Washburn (1930) presented the most up-to-date information on broom sorghum. Compared to earlier publications, they devoted more attention to cultivation, use and marketing.

Karper et al. (1932) reported results from agronomic experiments conducted in Texas with grain sorghum, while Quinby et al. (1934) published results from agronomic experiments with forage sorghum. Similar results obtained in Oklahoma were reported by Kiltz et al. (1933).

In California, cultivation recommendations for sorghum were made by Hendry (1933); in Kansas, information on forage sorghum cultivation was published by Getty (1934). Also in Kansas in the same year, valuable information on sorghum classification was published by Swanson and Laude. In South Dakota, Hume and Franzke (1934) also published experimental results for sorghum.

In Europe, sorghum did not attract much attention, with the exception of the Mediterranean coast. Assumptions about this crop made before 1850 were not based on clear data; only after that year were more complex descriptions of cultivated sorghum forms carried out. These descriptions, however, were largely based on the botany of the species rather than its agronomy.

Sorghum cultivation in Europe has been known since the 15th century. For grain production, sorghum hybrids are grown — hybrids that appeared following the discovery by Stephens of androsterile and fertility-restoring biotypes, which are 30–40% more productive than open-pollinated varieties (Zamfirescu et al., 1965).

In France, as in England, researchers were interested in sorghum mainly due to the African colonies present on their territories. For a considerable period, sorghum did not attract interest or effort from French botanists to study this species.

There are, however, references to sorghum in the literature; the oldest important French work from a classification standpoint is that of Sagot, published posthumously by Raoul (1893). This work presents data on Algerian agriculture but lacks specific descriptions of the varieties used, only indicating the provenance zone of the cultivar: "shalagoova sorghum from Zululand."

Dumas (1905) and Jumelle (1912) published descriptions of varieties cultivated by indigenous peoples along the Niger and its tributaries in Senegal. Géze (1923) published an article reviewing previous classifications. Piedallu (1923) wrote a chapter on the history of sorghum, mentioning extensive sorghum research available in European libraries.

In Romania, the first information about sorghum appears in the literature as early as 1943, when Popescu-Sanitaru noted that sweet sorghum, compared to grain and broom sorghum, has longer internodes. The last internode bearing the inflorescence may be straight or curved downward by 180°. It is low in sugars and rich in mineral salts, being removed at harvest time.

Sweet sorghum is a species with a long tradition in Romanian agriculture. During World War II, the plant was cultivated in the regions of Bessarabia, Dobruja, Prahova, the Danube Plain and the Banat.

In the Banat, in the lowland areas, the cultivation and processing of sweet sorghum has been known in the villages of Uivar, Pustinis, Liebling, Foeni, Ionel, Covacita, etc. since the beginning of the 1940s.

In 1942, in the workshop of Ludwig Josif from Uivar, craftsman Table Livius made two wooden locust-wood rollers for pressing sorghum stalks. As compensation, Table received a panicle with small, yellow-brownish, dense and shattering-resistant seeds.

The sorghum was carefully multiplied by the Table family in the commune of Pustinis. In 1946, upon the craftsman's return from military service, he found about 600 m² of crop growing and built a manual roller press of wooden rolls for juice extraction. In 1947, he built a press with metal rollers powered by a thermal engine (Sedling brand), with a juice capacity of 3–4 tonnes/day. The juice obtained was concentrated by boiling in a cast-iron cauldron to a high consistency, then allowed to rest for 1–6 days, during which a large mass of sorghum sugar crystals formed. This was then washed of molasses, divided, ground and used to sweeten various foods (homemade pastries, tea, etc.).

The cellulosic part obtained after pressing the stalks was used as feed for horses, and when ensiled, as feed for dairy cows, demonstrating increased milk production and fat content. Seeds were used for poultry feed.

This valued activity spread quickly to neighboring communes (Otelec, Ionel, Foeni, Rauti, Sinmartinul-Maghiar, etc.) and throughout the Banat region.

From 1948, the next step in sweet sorghum juice processing became known — the alcohol fermentation stage. However, in 1951, legal provisions prohibiting alcohol and alcohol-producing plants also banned the cultivation of sweet sorghum; at the height of the season, the sorghum stalk pressing workshop in the commune of Pustinis was sealed. Thus, cultivation of this plant was abandoned. To preserve the variety, the Table family cultivated this type of sorghum year after year in their garden, in isolated plots, and found ingenious solutions even after relocating to Timisoara, using a private garden.

Both the first years of cultivation (1942–1951) and the subsequent period up to 1982 constitute a long period of acclimatization of the plant to the climatic conditions of the Banat Plain, resulting in a variety with well-defined morphological and biological characteristics, superior to other genotypes.

In the autumn of 1982, retired craftsman Table presented the advantages of sweet sorghum cultivation — a plant he had passionately maintained for years — along with a carbohydrate concentrate produced in his kitchen. It was decided that the Institute of Hygiene in Timisoara, within its food chemistry laboratory, should study the superior valorization of this local plant. The Institute of Hygiene drew up, in 1983, the first conclusions with the results of preliminary research on the valorization of plants in food and industry, in collaboration with the Chemistry Center and the Agronomic Institute of Timisoara.

In 1983, in Giroc, the first hectare of this crop was established using seed stock received from retired craftsman Table (using 5.3 kg seeds/ha). Sowing was carried out on July 20, 1983. The green mass yield obtained was 80 t/ha and 1,500 kg grain/ha — yields recorded under drought conditions with only a single mechanical inter-row cultivation.

In 1984, cultivation was extended to Topolavatu Mare, Honorici, Dumbravita, Ciarda Rosie, Mosnita Noua and Recas.

Also in that year, with the support of the "Solventul" industrial enterprise, one of the maize grain mills was adapted as a press for sweet sorghum stalks and installed at Topolavatu Mare.

Harvesting and pressing of the stalks were carried out in the period December 18–22, 1984. The juice obtained (about 2 tonnes) was used in an ethanol production experiment at the spirit section of the Solventul enterprise.

For better and more efficient collaboration between growers and researchers, in 1985 it was decided to establish a model experimental crop at the Timisoara Agro-Industrial Unit (U.A.I.T.). The crop was located in the area between Calea Aradului and Torontalului, using seed stock from craftsman Table. An average green mass yield of about 86.7 t/ha was obtained. The juice obtained by pressing the stalks had a total soluble solids concentration of 17–21.5%, of which 44.5–48.3% was sucrose, glucose and fructose.

At the Scientific Research and Technological Engineering Institute for Agricultural Machines and Equipment (I.C.S.I.T.M.U.A.), Timisoara branch (for designing the stalk pressing installation) and at the Research and Design Institute for Sweet Substances at Fundulea, research was initiated in this field. The high capacity of biosynthetic chlorophyll activity in sweet sorghum, which uses solar energy more efficiently than maize, was demonstrated.

In addition, the species — having a long growing season — also constitutes a source of biologically active constituents (sterols, vitamins, enzymes, etc.) for animal feed during late autumn and winter.

News of the exceptional crop being cultivated at Timisoara spread quickly, leading prominent specialists from across the country to visit and appreciate the work being done by agricultural units and researchers in Timisoara, in promoting this local variety of Sorghum saccharatum.

Subsequently, crops were grown year after year in Timisoara with nearly consistent results, as the city became a model center for disseminating knowledge in sweet sorghum cultivation technology — distributing written materials and facilitating experience exchanges with the technical management of agricultural units in the county.

In parallel, studies and research were developed covering:

- Systematics, morphology, pathogenesis and cultivation technology, by I.C.C.P.T. Fundulea and the Agronomic Institute Timisoara
- Modern techniques in explant in vitro culture and genetic engineering for rapid multiplication and improvement of the Timis sweet sorghum population, by the Center for Biological Research in Cluj
- Design of technological equipment for juice extraction from stalks, by I.C.S.I.T.M.U.A. Timisoara branch, culminating in the construction of an experimental model by the Mechanical Enterprise Timisoara in October 1988
- Chemistry and technology of food products from the juice and seeds of the plant, by the Institute of Hygiene and Public Health Timisoara, in collaboration with the Chemistry Center, the Agronomic Institute, local enterprises (Beer, Sugar, Fructus, Kandia) and the Solventul enterprise

The main objectives that shaped the breeding program from the outset were: precocity, increased production capacity, tolerance to soil alkalinity and salinity, increased tolerance to aphid attack, and improvement of grain quality and the rest of the plant (reducing tannin content while increasing protein, starch and oil content in the grain, and reducing hydrocyanic acid and tannin content in the green plant).

For the production of hybrid sorghum seed, scientific schemes were established for the methodology and technique of seed production, concerning the maintenance and multiplication of parental lines and the technology for producing hybrid seed with high varietal purity. For this purpose, research was conducted on the flowering biology of sorghum lines, determining the average flowering duration and the rate of panicle flowering, stigma receptivity, and the optimal time for panicle pollination for lines in the seed production program.

Based on the results obtained, a method was established for ensuring flowering synchronization between parental lines of hybrids with staggered flowering dates. Over the years, observations were made by specialists on the vegetative phases, especially the sowing-to-flowering period for parental forms, as well as methods for eliminating the flowering lag in certain hybrids. Determinations were also made regarding the duration of stigma emergence and stigma receptivity (Manoliu et al., 1965).

To meet immediate practical requirements closely linked to the efficiency of hybrid seed production operations in Romania, research was initiated at I.C.C.P.T. Fundulea from 1963 onward on the main aspects of flowering biology and pollination of sorghum lines. Both androsterile lines, their fertile analogues, and fertility-restoring lines were monitored (Sarca et al., 1976). The results highlighted flowering lags between component lines of certain hybrids (Covor et al., 1964).

Through collaboration between the Center for Biological Research and the Institute for Isotopic and Molecular Technology in Cluj-Napoca, and the Institute for Cereals and Industrial Crops Research at Fundulea, a series of parameters necessary for the electro-fusion of cereal protoplasts were identified (Turcu et al., 1986; Lucaciu et al., 1988).

At I.C.C.P.T. Fundulea, some sorghum hybrids and local populations were tested in comparative trials. Observations showed weak germination in local populations, but the richest foliage was achieved by a local population, followed by a hybrid (Rusu et al., 1986). Subsequently, multiple experiments were conducted on the adaptability to pedoclimatic conditions of domestic sorghum varieties and hybrids, with results showing that the studied genotypes performed well in relation to environmental factors (Antohe et al., 1989).

Compared to maize, the leaf area and root system of sorghum are twice as well developed (Bilteanu, 1991), meaning sorghum can serve as an alternative to maize, being an economical option under drought conditions (Antohe, 2007). Furthermore, research conducted on some grain sorghum genotypes on irrigated sandy soils concluded that sorghum is recommended for these soils, as yields obtained are higher compared to other crops (Draghici, 2007, 2009).

Scientific research in Romania on plant cultivation technologies began with the establishment of I.C.A.R. (the Agronomic Research Institute of Romania), organized, coordinated and led by the great scholar Gheorghe Ionescu-Sisesti. After the establishment of I.C.C.P.T. Fundulea (the Central Research Institute for Industrial Crops) in 1957, sorghum became one of the species studied in terms of productivity and quality, breeding, and use for food, feed and as a raw material for the chemical industry.

Research conducted at I.N.C.D.A. Fundulea (the National Agricultural Research and Development Institute) and in the experimental fields of the Faculties of Agriculture in Bucharest, Iasi, Craiova and Timisoara focused on establishing and optimizing the technological sequences for sorghum cultivation.

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CHAPTER II

SYSTEMATICS AND DISTRIBUTION OF THE SPECIES

2.1. SYSTEMATICS OF THE SPECIES

Cultivated sorghum belongs to the family Poaceae (Gramineae), genus Sorghum, species Sorghum bicolor (L.) Moench.

Sorghum is a species with remarkable genetic variability, which makes it difficult to classify. Its systematics have attracted the attention of numerous researchers without reaching consensus, a situation generated by the numerous cultivated forms and the great similarities among them.

In 1753, researcher Linné described cultivated sorghum as a species, naming it Holcus sorghum, which he placed in the tribe Avenae.

For the first time, the term "Sorghum" was used by Adanson (1784), who replaced the old name given by Linné. The name derives from the Latin word "Surgo" and was assigned to a genus in the family Poaceae (Gramineae), tribe Andropogoneae (Antohe et al., 2006).

Brotero (1804) classified sorghum as belonging to the genus Andropogon, naming the cultivated species Andropogon sorghum and the wild form Andropogon halepense.

Persoon C.H. (1805) returned to the earlier classification in which sorghum belonged to the genus Sorghum, naming the cultivated species Sorghum vulgare.

Later, in 1874, Moench made a clear distinction between the two genera, Holcus and Sorghum, individualizing the latter through his description, specifying that the inflorescence contains an even number of spikelets, of which one is sessile and fertile, while the second spikelet is short-pedicellate and lacks male floral organs (androecium).

Körnicke–Werner (1885) adopted the name given by Brotero and further divided the cultivated species according to the morphological characters of the panicle and grains into two subspecies:

- A. s. (Andropogon sorghum) effusum Körnicke — with an open (loose) panicle
- A. s. (Andropogon sorghum) contractum Körnicke — with a dense panicle

Zamfirescu et al. (1965) note that each of these subspecies is divided into two groups based on the length of the main panicle axis (short or long) and the panicle outline (spherical, oval or elongated), with varieties identified by other characters such as the length of secondary branches, color of glumes and grains.

The monographer Snowden (cited by Jukovski, 1950 and Zamfirescu, 1965) proposed a new classification of the genus into sections (Parasorghum and Eusorghum), subsections and species series (the spontanea series — including sudangrass — and the sativa series encompassing cultivated species).

Angelini F. (1965) presented his own classification of the genus Sorghum into:

Section Eusorghum containing two subsections:

- Subsection Halepensia — comprising perennial forms with rhizomes (Sorghum halepense)
- Subsection Arundinacea — comprising annual cultivated forms, in turn divided into two series:
- Series Sativa (Sorghum vulgare, Sorghum saccharatum)
- Series Spontanea (Sorghum sudanense)

The most widely accepted classification of sorghum systematics places it in the family Poaceae (Gramineae), tribe Andropogoneae, genus Sorghum, with 31 annual and perennial species.

According to Spaldon (1982, updated), annual forms belong to the species Sorghum bicolor (L.) Moench (synonym Sorghum vulgare), with 2n = 20 chromosomes.

Depending on the mode of use, this species includes the following varieties:

- Sorghum bicolor, var. eusorghum — grain sorghum
- Sorghum bicolor, var. technicum — broom sorghum
- Sorghum bicolor, var. saccharatum — sweet sorghum
- Sorghum bicolor, var. sudanense — forage sorghum (sudangrass)

Sweet sorghum (Sorghum saccharatum) is classified according to panicle shape into two subspecies:

- subsp. effusum — with a loose (open) panicle
- subsp. contractum — with a compact panicle

Other species also cultivated for grain include:

- Sorghum guinense — Guinea sorghum or West African sorghum
- Sorghum bantum — Negro sorghum or Central African sorghum
- Sorghum cafer — Kafir sorghum or South American sorghum
- Sorghum durra — typical grain sorghum or Afro-Asiatic sorghum (milo, durra)
- Sorghum propinquum — Asian or Chinese sorghum
- Sorghum feterita — cultivated in Sudan
- Sorghum shallu — cultivated in India and West Africa

The tribe Andropogoneae, to which both sorghum and maize belong, contains 46 subtribes. The subtribe Sorghastrae, which includes the genus Sorghum, is the most relevant to sorghum systematics.

According to Garber (1950, 1954), the genus Sorghum has only 25 recognized species, taxonomically classified into six subgenera or sections:

1. Subgenus Eusorghum (n=10 chromosomes) — widespread in Africa, Asia, America and Australia; corresponds to the section Eusorghum in Snowden's 1936 classification

2. Subgenus Chaetosorghum (n=10 and n=20 chromosomes) — found in Australia

3. Subgenus Heterosorghum (n=10 and n=20 chromosomes) — found in the Philippines, New Guinea and Australia

4. Subgenus Sorghastrum (n=10 chromosomes) — found in America and Africa

5. Subgenus Para-Sorghum (n=5 chromosomes) — found in Africa, America, Guatemala, Asia, Australia and Mexico

6. Subgenus Stiposorghum (n=5 chromosomes) — found in Australia

Sorghum species thus have a chromosome number of 2n = 10, 20, 30 or 40 (Garber, 1950; Lazarides et al., 1991).

Section Eusorghum includes cultivated sorghum (Sorghum bicolor) and the wild species Sorghum almum Parodi, Sorghum propinquum (Kunth) Hitch. and Sorghum halepense (L.) Pers. Species of section Eusorghum have a wide range across Africa and South Asia (Duvall and Doebley, 1990).

The full list of 28 recognized Sorghum species and their geographic distributions includes:

1. S. amplum — northwestern Australia; 2. S. angustum — Queensland; 3. S. arundinaceum — Africa, Indian subcontinent, Madagascar, western Indian Ocean islands; 4. S. bicolor — cultivated sorghum (durra, jowari, milo), originating from the African Sahel; 5. S. brachypodum — Northern Territory, Australia; 6. S. bulbosum — northern and western Australia; 7. S. burmahicum — Thailand, Myanmar; 8. S. controversum — India; 9. S. × drummondii — Sahel and West Africa; 10. S. ecarinatum — northern and western Australia; 11. S. exstans — Northern Territory, Australia; 12. S. grande — northeastern Australia (Queensland); 13. S. halepense (Johnsongrass) — North Africa, eastern Atlantic islands, southern Asia from Lebanon to Vietnam; naturalized in East Asia, Australia and America; 14. S. interjectum — northern and western Australia; 15. S. intrans — northern and western Australia; 16. S. laxiflorum — Philippines, Sunda Islands, Sulawesi, New Guinea, northern Australia; 17. S. leiocladum — Queensland, New South Wales, Victoria (Australia); 18. S. macrospermum — Northern Territory, Australia; 19. S. matarankense — northern and western Australia; 20. S. nitidum — East Asia, Indian subcontinent, Southeast Asia, New Guinea, Micronesia; 21. S. plumosum — Australia, New Guinea, Indonesia; 22. S. propinquum — China, Indian subcontinent, Southeast Asia, New Guinea, Micronesia, Cook Islands; 23. S. purpureosericeum — Sahel, Tanzania, Yemen, Oman, India; 24. S. stipoideum — northern and western Australia; 25. S. timorense — Sunda Islands, Maluku, New Guinea, northern Australia; 26. S. trichocladum — Mexico, Guatemala, Honduras; 27. S. versicolor — eastern and southern Africa from Ethiopia to Namibia, Oman; 28. S. virgatum — dry zones from Senegal to the Levant.

By chromosome number, sorghum species group as follows:

- Diploid forms (2n=2x=10; n=5): S. purpureo-sericeum, S. versicolor, S. intrans, S. brevicollosum, S. stipoideum (Australia)
- Tetraploid forms (2n=4x=20; n=10): S. virgatum (Tunis grass), S. effusum (Cameroon grass), S. verticiliflorum (Fabucki grass, Africa), S. leiocladum, S. nitidum, S. plumosum (Australia), S. propinquum (Asia) — a rhizomatous species with small, hard seeds from Asia, Indonesia and the Philippines, which contributed to the formation of Chinese sorghum
- Octoploid forms (2n=8x=40; n=20): S. halepense (Johnsongrass) — a tetraploid derived from the crossing of S. arundinaceum and S. propinquum; S. macrospermum; S. laxiflorum (Australia); S. almum (Columbus grass) — originating in Argentina, arising from crosses between S. bicolor and S. halepense

The taxonomic classification of sorghum is made difficult by its extreme genetic diversity.

In the classification by Harlan and de Wet (1972), 15 types are established, including five primary races: bicolor, guinea, caudatum, kafir and durra, and 10 intermediate races representing possible combinations among the primary races (bicolor-guinea, bicolor-caudatum, etc.).

From this perspective, sweet sorghum is considered the primary form of the species Sorghum bicolor. It possesses an abundance of sweet juice with multiple uses.

From crossing grain sorghum with sweet sorghum, new varieties with a wide range of practical applications have been obtained: forage, food, energy raw material, etc. (Antohe, 2007).

With the use of germplasm from the feterita, hegari and kafir types in sorghum breeding programs, and the durra-kafir combination opening the way for the use of androsterility and fertility restoration, sweet sorghum — in addition to local populations and open-pollinated varieties in cultivation — now also includes hybrids that are expanding in cultivation.

Grain sorghum is becoming a viable alternative to maize in areas where rainfall during its growing season is increasingly insufficient or very unevenly distributed relative to the growing period and the plant's water requirements (southern and central Oltenia, southern and central Moldova, Bărăgan, Dobruja, etc.) (Matei, 2013).

2.2. DISTRIBUTION OF THE SPECIES

The genus Sorghum has spread almost continuously from southern Africa to the subtropical zone of Australia, where it arrived with European colonization of the region.

The greatest diversity of cultivated and wild sorghum forms is found in the northeastern region of the African continent: Egypt, Ethiopia, Somalia and Sudan.

Sorghum bicolor subsp. halepense is widely distributed in the Mediterranean Region and extends to the islands of Southeast Asia. This species contains weeds frequently encountered in the areas bordering the Mediterranean Sea and the Tropical Region. According to a study by De Wet (1967), this genus is divided into two ecotypes, morphologically distinct: a Mediterranean ecotype and a tropical ecotype. The Mediterranean ecotype is represented by small plants with narrow leaves, having 2n = 40 chromosomes.

These weeds extend from Asia Minor to the mountains of western Pakistan, where they are replaced by the more robust tropical ecotype. These large-leaved, tall weeds are found in great numbers in southern India, and their morphological characteristics suggest that the tropical ecotype arose due to the presence of cultivated sorghum in this area.

In southern India and Southeast Asia, there is also another weed of the tropical ecotype, a chromosomal race with 2n = 20. Hackel (1885) and Körnicke (1885) suggested that cultivated sorghum may have derived from Sorghum bicolor subsp. halepense. However, Piper (1915) explained that cultivated sorghum could not have derived from rhizomatous sorghum forms.

Sorghum bicolor subsp. bicolor includes all cultivated sorghum forms, including weeds and semi-wild sorghum forms. Weeds of Sorghum bicolor from tropical and subtropical zones of West Africa belong to var. arundinaceum. They are found spread from Sierra Leone along the humid zone, frequently occurring around waste areas and often invading cultivated fields.

The variety aethiopicum extends from north of the equator, from northern Nigeria, eastward to Somalia and along the Nile Valley to Cairo. This variety is represented by weeds that grow naturally along riverbanks but can also be found sporadically in agricultural fields. In westward distribution, var. aethiopicum overlaps with var. arundinaceum, and hybridization between them produces other cultivars typical of northern Nigeria.

Cultivated sorghum has a wide distribution due to its use in human nutrition, especially in semi-arid zones where pedoclimatic conditions limit high-performance agriculture. Such situations are found mainly in Africa, Asia and Latin America, which are frequently affected by drought.

Currently, sorghum is a cereal of high importance, ranking among the principal grain-producing cereals in the world, with an annual production of 57,893,378 tonnes.

TABLE 2.1 — Average Production of Principal Cereals Worldwide, 2015–2019 (FAO, 2021)

Average yield (kg/ha): 2015 / 2016 / 2017 / 2018 / 2019 | Total annual production (tonnes)

- Maize: 5,503 / 5,738 / 5,744 / 5,715 / 5,824 | 1,148,487,291
- Rice: 4,569 / 4,551 / 4,557 / 4,609 / 4,662 | 755,473,800
- Wheat: 3,321 / 3,418 / 3,538 / 3,427 / 3,547 | 765,789,635
- Barley: 2,964 / 3,015 / 3,101 / 2,910 / 3,108 | 158,979,610
- Sorghum: 1,431 / 1,412 / 1,426 / 1,445 / — | 57,893,378

The species ranks fifth in the world in terms of cultivated area (after wheat, maize, rice and barley) and is cultivated in more than 85 countries.

TABLE 2.2 — Cultivated Area of Principal Cereals Worldwide, 2015–2019 (FAO, 2021) [thousands of ha]

- Total cereals: 723,003 / 728,636 / 729,246 / 726,547 / 724,262
- Wheat: 223,414 / 219,018 / 218,300 / 213,982 / 215,902
- Maize: 191,276 / 196,488 / 198,220 / 196,798 / 197,204
- Rice: 160,207 / 162,516 / 164,948 / 165,522 / 162,056
- Barley: 49,838 / 48,374 / 47,878 / 48,028 / 51,150
- Sorghum: 41,655 / 44,358 / 41,097 / 42,347 / 40,075

The African continent is the largest sorghum grower, holding more than half of the world's cultivated area. The largest sorghum growers are Niger, with a cultivated area of 3,747,664 ha and total production of 1,896,638 tonnes (2019), and Sudan, with a cultivated area of 6,827,520 ha and total production of 3,714,000 tonnes (FAO, 2021).

In the continental countries of Asia, secondary centers of sorghum origin are located in India and China. The sorghum-cultivated area in Asia is approximately equal to that in America, at around 5–6 million hectares.

TABLE 2.3 — Sorghum Cultivated Area Worldwide, 2015–2019 (FAO, 2021) [thousands of ha]

- Total sorghum: 41,655 / 44,358 / 41,097 / 42,347 / 40,075
- Africa: 25,823 / 30,008 / 27,941 / 29,923 / 28,427
- Asia: 7,745 / 7,439 / 7,028 / 6,464 / 5,636
- America: 7,008 / 5,985 / 5,453 / 5,250 / 5,138
- Oceania: 734 / 522 / 369 / 464 / 551
- Europe: 345 / 405 / 305 / — / —

India has the largest cultivated area with sorghum at approximately 4 million hectares, with a total annual production of 3,475,410 tonnes. This country ranks 3rd in the world in annual production, after the USA and Sudan.

In the United States, grain and green-mass sorghum occupies about 12% of arable land, being cultivated on 1,891,930 ha, from which an annual total production of 8,673,480 tonnes is harvested (FAO, 2021).

In Latin America, as a distinct wild form that has been taken into cultivation, Sorghum almum (a tetraploid formed by crossing between cultivated sorghum and Johnsongrass) is found, while in Australia, wild forms from the subgenera Stipo-Sorghum and Para-Sorghum are encountered.

In Europe, although sorghum was introduced in the 15th century, it did not spread rapidly. The cultivated area in Europe is 322,494 ha, with a total annual production of 1,369,774 tonnes.

Although EU member countries cultivate about 60% of Europe's total sorghum area, they together achieve about 75% of the continent's total production. Nevertheless, this quantity is insufficient for the Community Bloc, as the estimated sorghum requirement for EU needs stands at approximately 1,200,000 tonnes/year.

The principal EU growing countries are France, Italy, Hungary and Romania, which are also the main European sorghum producers.

TABLE 2.4 — Principal Sorghum-Growing Countries in the EU, 2019 (FAO, 2021)

Country | Area (ha) | Avg. yield (kg/ha) | Total production (tonnes)

Total Europe: 322,494 / 4,247 / 1,369,774

Total EU: 190,020 / 5,379 / 1,022,120

France: 83,090 / 5,090 / 422,900

Italy: 46,800 / 6,899 / 322,850

Hungary: 23,320 / 5,416 / 126,280

Romania: 15,710 / 3,820 / 60,010

Bulgaria: 7,040 / 3,298 / 23,220

Spain: 6,580 / 3,922 / 25,730

Austria: 3,940 / 7,548 / 29,740

Greece: 2,360 / 3,153 / 7,440

Slovakia: 1,070 / 3,206 / 3,430

Slovenia: 130 / 3,023 / 510

In the context of increasingly evident climate change and global policies to find alternatives to fossil fuels, sweet sorghum stands out as the best crop for co-production of bioethanol and biopower. In the near future, a major increase in demand for liquid transport fuels and energy, or for the development of sweet sorghum biorefineries, is anticipated.

Given that sweet sorghum has no soil preferences, has low moisture requirements, is adaptable to very varied climatic conditions, and achieves bioethanol yields similar to sugarcane, it can be anticipated that this crop has a significant potential for expanding its cultivated area worldwide (Pochiscanu et al., 2016).

CHAPTER III

GENETICS AND BREEDING OF THE SPECIES

3.1. GENERAL CONSIDERATIONS

Sorghum (Sorghum vulgare Pers. syn. Sorghum bicolor L.) is a herbaceous plant of the family Poaceae, originating from Africa, where it still grows wild over extensive areas. In Eurasia it has been cultivated since antiquity (in Assyria and India, the earliest attestations date from the 8th century BCE).

The wide adaptability of sorghum and its multiple uses are linked to its natural genetic diversity and phenotypic plasticity. It exhibits a wide range of forms resistant to abiotic and biotic stresses.

Over the past fifty years, due to genetic advances, the average yield of grain sorghum has doubled, increasing from 3 t/ha to 6 t/ha (ARVALIS — Plant Sector Institute).

Sorghum is in full expansion: with low water consumption, it has multiple uses, from animal feed to human food. Over the past two decades, sorghum has been gaining ground in Europe at the expense of other crops less adapted to evident climate change.

In terms of suitability for cultivation, sorghum is first and foremost a crop that adapts very well to climate change, with high drought tolerance. Secondly, it allows farmers to obtain reliable yields, ensuring diversification of crop rotation. Sorghum can be an advantageous alternative crop when the normal production of other cereals is affected by unfavorable weather conditions or pests. For animal breeders, sorghum is also a means of ensuring a supply of high-quality fodder.

The main objectives of the sorghum breeding program have been: increasing production capacity, tolerance to soil alkalinity and salinity, increasing tolerance to aphid attack, and improving grain quality and the rest of the plant (reducing tannin content while increasing protein, starch and oil content in the grain, and reducing hydrocyanic acid and tannin content in the green plant).

Among the earliest works on sorghum genetics are those of Graham (1916). These were followed by other landmark studies on the main achievements in this field, published by Magness (1936), Quinby and Martin (1954), Poehlman (1959), Quinby (1961), Schertz and Stephens (1966), Quinby and Schertz (1970), and more recently by the thematic bibliographies produced by SMIC–ICRISAT (Sorghum and Millet Information Center — International Crops Research Institute for the Semi-Arid Tropics), India.

Cultivated sorghum has a haploid set of 10 chromosomes. The linkage groups for the 10 chromosomes are incompletely known (Doggett, 1970). Studies by Webster (1977, 1979, 1982) provided new data on identifying chromosomal positions and the degree of linkage of genes D, Rs, P, Y10, Lg and Ts, which condition certain characters of the sweet sorghum plant, such as stalk juiciness, seedling color, etc.

Acheampong et al. (1984) classified the chromosome numbers for the subgenera of the genus Sorghum (Table 3.1):

TABLE 3.1 — Primary, Secondary and Tertiary Gene Pools in Genus Sorghum and Chromosome Numbers (Acheampong et al., 1984)

- Primary gene pool: Sorghum bicolor (diploid, 2n=20, x=10); Sorghum halepense (tetraploid, 2n=40, x=20)
- Secondary gene pool: various Eusorghum section species
- Tertiary gene pool: Sect. Parasorghum (2n=10,20; x=5,10); Sect. Stiposorghum (2n=10,20; x=5,10); Sect. Halepensia (2n=40,20; x=20,10); Sect. Chaetosorghum (2n=40,20; x=20,10)

Sorghum was the first cereal whose genome was fully sequenced in 2006, which conferred new rates of progress in breeding (Antohe, 2007), its genome having a size of approximately 740 Mb (Paterson et al., 2009).

3.2. GENETIC RESOURCES IN SORGHUM

The first steps toward building a world sorghum germplasm collection were taken in India after 1967, when over 16,000 accessions were collected from several important sorghum-growing regions in numerous countries. The accessions were analyzed and classified with the symbol IS (International Sorghum) and a sequential number. Some of these accessions (nearly 9,000) were transferred to ICRISAT, while the others lost their germination.

The ICRISAT collection was supplemented with 3,000 accessions from Purdue University, the National Seed Storage Laboratory at Fort Collins (USA) and Puerto Rico in 1974, at the recommendations of the Consultative Committee on Sorghum and Millets. These encompass most of the native diversity of cultivated sorghum. Nevertheless, much of the diversity of wild sorghum races is underrepresented in these collections.

Despite the significant number of collections and gene banks, a large portion of sorghum diversity remains unexplored. In the last decade, enormous progress has been made in building the molecular and genomic foundation needed to increase understanding of genome diversity in sorghum, gene reserves, and ultimately to link this information to species improvement.

Sorghum has been widely investigated to understand the taxonomic relationships and evolution of the crop. Early studies focused on morphology, cytology and distribution data, mainly of the African wild sorghum component (Snowden, 1955; Liang and Casady, 1966; de Wet et al., 1970; de Wet and Huckabay, 1967; de Wet and Harlan 1971; de Wet, 1978; Harlan, 1992), which helped circumscribe the limits of known sorghum species and explain their origin and domestication process.

Cultivated sorghum (Sorghum bicolor) is particularly vulnerable to risks associated with gene flow from several wild species (weeds) such as Sorghum halepense, Sorghum bicolor ssp. drummondii and Sorghum almum.

Sorghum halepense and Sorghum bicolor L. (Moench.) are common wild species in many sorghum-growing zones worldwide. Sorghum varieties with adaptive traits developed through conventional breeding or new transgenesis present agronomic and ecological risks if these traits are transferred to wild relatives/species. Knowledge of the nature and characteristics of gene flow between different sorghum species is limited and data are very varied.

Gene flow is one of the main factors of speciation, and some of the most important crops today are the product of distant hybridizations (Arnold, 1992). Approximately one-quarter of characterized plant species are the result of interspecific and intergeneric hybridization (Mallet, 2005).

Cultivated sorghum (Sorghum bicolor (L.) Moench., 2n = 2x = 20) is a classic example in which gene flow from wild weedy relatives presents both ecological and agronomic problems. It can hybridize with its relatives: S. halepense (2n = 4x = 40), S. bicolor ssp. drummondii (Nees ex Steud.) De Wet ex Davidse (2n = 2x = 20), and S. almum Parodi (2n = 4x = 40).

Sorghum halepense is an important perennial weed/wild relative of cultivated forage sorghum, and also a highly invasive weed along roadsides and in other disturbed areas, with worldwide distribution. Its extensive rhizome and stolon system, as well as its high seed production rate, make it extremely invasive and difficult to eradicate. This species presents several harmful characteristics: toxicity to grazing animals, fire risk during summer, and competition that excludes other plants. It reduces soil fertility, can harbor crop pathogens, and is known to have allergenic effects. It is considered a serious weed in 53 countries and is encountered in a wide range of field crops.

Sorghum bicolor ssp. drummondii is a perennial species that produces rhizomes, but these are often intolerant of winter frosts, so it does not represent a significant problem, though it is encountered in production fields.

Sorghum almum Parodi (2n = 4x = 40) is a hybrid between S. halepense and S. bicolor, which produces short rhizomes and is cultivated as a forage species (USDA-NRCS, 2016).

Billot et al. (2013) genotyped a large global sorghum collection (3,367 accessions), including landraces (89.5%), breeding lines or advanced varieties (8.3%), wild/weed types (2.0%) and unknowns (0.1%) using SSR technique. Seventeen genetic markers produced alleles unique to wild/weed accessions; 40 out of 783 alleles were unique to wild species, of which three were found in a single Sorghum propinquum accession; wild types and weeds encompassed 57–65% of detected alleles, without a clear separation between wild and cultivated types, showing that there is considerable gene flow between them.

In conclusion, wild sorghum from northeastern and central Africa shows genetics much more similar to cultivated varieties than to wild sorghum from northwestern or southern Africa, confirming that this sorghum is ancestral to domesticated sorghum. Sorghum halepense most likely originated through autopolyploidy or segmental allopolyploidy.

Cultivated sorghum lost diversity during domestication. Nevertheless, many evaluations have indicated that sorghum has great diversity. Multiple origins for domesticated sorghum, cross-pollination between local and selected forms, and pollination between domestic varieties and extremely variable wild species are considered contributing factors to the extensive genetic diversity observed in sorghum (Doggett, 1988).

Muraya et al. (2011) showed that long-distance seed-mediated gene flow leads to a low regional level of sorghum differentiation, reflecting the importance of human intervention in shaping the structure and diversity of populations and genetic flow, which can make geographic boundaries irrelevant.

3.3. GENE POOL AND CONSERVATION PERSPECTIVES

The threat of genetic erosion in landraces due to the creation of varieties and hybrids has led to increased collection and conservation efforts worldwide. Concurrently, there has been a growing awareness of the importance of wild species in crop improvement, and national and international gene banks have begun establishing collections with wild species. Currently, ICRISAT holds 458 accessions of wild sorghum belonging to 13 species, in addition to 37,904 accessions of cultivated sorghum from 91 countries.

Harlan and de Wet (1971) proposed three informal categories or gene pools (primary, secondary and tertiary) based on the ease of use of wild sorghum in crop improvement:

- The primary gene pool includes all cultivated sorghum and its wild/weedy relatives with 2n = 20 chromosomes (S. bicolor complex) alongside S. propinquum, a perennial diploid species
- The secondary gene pool comprises S. halepense, an autotetraploid species reported to have likely arisen from a cross between S. propinquum and S. verticilliflorum (Doggett, 1988)
- The tertiary gene pool contains members of all other sorghum sections (2n = 20, 30, 40), as well as related genera — Saccharum, Zea, Cliestachne and Sorghastrum

For sorghum, species from the primary and secondary gene pools are adequately represented in the few ex situ collections, but since all species are relatively widespread, they do not present a conservation priority (Maxted et al., 2006).

However, taking into account the growing recognition of the potential and significance of wild species in sorghum improvement, gaps in existing collections should be analyzed and ex situ research should be conducted in relation to the diversity hotspots of these wild species, in order to identify and prioritize targeted collection of underrepresented species across their full distribution range.

Historically, genetic resources have been conserved mainly using ex situ methods, with the greatest attention given to collecting and maintaining landraces, traditional varieties, improved lines and genetic stocks (Hawkes et al., 2000; Smith et al., 2003).

Recent research has questioned whether the diversity of local sources can be effectively conserved ex situ due to the genetic bottleneck associated with sampling and multiplication/regeneration in gene banks, and the genetic diversity that changes constantly and relatively rapidly within populations (Negri and Tiranti, 2010). Similarly, in situ conservation should be the primary conservation strategy, as it promotes natural gene exchange and the continuous evolution of landrace populations and wild crops (Maxted et al., 1997a; Stolton et al., 2006; Negri et al., 2009).

The availability of adequate genetic variation is a fundamental prerequisite for genetic improvement of any crop species. Estimating genetic diversity and identifying groups with similar genotypes is important for the conservation, evaluation and use of genetic resources, for selecting possible gene sources that can improve variety performance, and for determining the uniqueness and distinctiveness of phenotypes and genotypes for the purpose of protecting breeders' intellectual property rights (Subudhi et al., 2002).

The use of genetic variability through artificial selection in breeding programs has led to major advances in agricultural productivity. However, for continued success in crop improvement, new sources of genetic variability must be incorporated into breeding programs to increase selection gains. The continuous use of elite germplasm by plant breeders tends to narrow genetic diversity and thus slows breeding progress and risks crop vulnerability (Hawkes et al., 2000).

Much of the research conducted on sorghum has focused on cultivated sorghum, while studies on wild sorghum are limited. The idea that wild sorghum could be used to broaden the adaptability of cultivated sorghum is based mainly on its wide range of ecological adaptation. S. arundinaceum proliferates in African tropical forests, while cultivated sorghum is very poorly adapted there (Harlan, 1992). S. virgatum is a form that extends to the edges of deserts, growing naturally beyond the cultivation zone and could be a source of drought tolerance. Seeds from the virgatum race are known to germinate at very high temperatures — an important trait for cultivation in high-temperature regions (Bramel-Cox and Cox, 1988). The same authors demonstrated the possibility of increasing sorghum productivity through gene transfer from the virgatum, arundinaceum and verticilliflorum forms.

The search for new sources of resistance genes is an important and ongoing process, as pest/pathogen populations continue to change their virulence. Sorghum is constrained by over 40 diseases and 150 pests (Jotwani et al., 1980).

Kamala et al. (2002) reported 36 new gene sources with resistance potential from wild/weed species that could be used to develop resistant varieties and to control Peronosclerospora sorghi Weston and Uppal (Shaw) (SDM), which causes major production losses. Only about 130 accessions were identified as resistant to pathogen attack, in a screening of over 16,000 accessions from the world sorghum collection at ICRISAT (Pande et al., 1997).

The distribution of resistance sources — Africa 80%; India 8%; USA and Australia 12% — seems to validate the widely accepted idea that resistance to many diseases/pests is not randomly distributed, but can be found in specific geographic/regional diversity centers where the host and pathogen have co-evolved (Leppik 1970; Harlan 1977).

Africa is the center of domestication as well as the primary center of crop diversity, while India is a secondary center. Africa is also probably the main center of pathogen diversity (Williams 1984), and is therefore also the region with greater diversity for resistance to SDM. Most races of S. halepense can be used directly in sorghum improvement to incorporate resistance to Peronosclerospora sorghi and to produce durable resistance for areas where the pathogen has high incidence. They can also be used to generate mapping/segregating populations to identify genes associated with resistance to Peronosclerospora sorghi and to enhance marker-assisted selection. Even if wild sorghum forms are not priority choices as gene sources for short-term production, their potential for improving resistance or tolerance to diseases and other stress types could prove useful.

3.4. GENETICS, GENOMICS AND REPRODUCTION OF SORGHUM

Sorghum halepense, a polyploid perennial wild species resulting from hybridization between S. bicolor and S. propinquum, can occasionally be used as forage and even as food (seeds/flour), but is also one of the world's most noxious weeds, spreading from its center of diversity in West Asia throughout much of Asia, Africa, Europe, North and South America and Australia. The potential for using its allelopathic properties is well documented by several researchers (Alsaadawi et al., 1986; Panasiuk et al., 1986; Einhellig and Souza, 1992; Ben-Hammouda et al., 1995; Forney and Foy, 1985); both Johnsongrass and sudangrass can reduce weed growth and contribute to reducing herbicide application.

Beyond plant resistance to unfavorable factors, recent evaluations of native Australian sorghum forms have revealed great diversity in grain morphology (seed size and shape), endosperm nature, distribution of protein bodies throughout the endosperm, and starch granule shape and size (Shapter et al., 2009).

The good starch properties of wild sorghum could be exploited for improving the efficiency of digestion of forage or food from cultivated sorghum (Dillon et al., 2007). Increased protein content in the starchy endosperm of wild species could also occur, with implications for digestibility for human and animal consumption, and may also be a small adaptation for supporting germination in soils with low nitrogen content (Shapter et al., 2009).

Sorghum is of particular importance as a diploid model for the Saccharinae clade, which includes complex polyploid forms recently formed such as Saccharum and Miscanthus (Heaton et al., 2008). Each of these polyploids has substantial genetic collinearity/synteny with sorghum (Ming et al., 1998; Kim et al., 2012), and Saccharum QTLs often show positional correspondence with those of sorghum (Ming et al., 2001, 2002).

One of the few crops adapted to all approaches proposed for renewable fuel production — i.e., from starch, sugar and/or cellulose — sorghum itself is currently second only to maize in the USA as a source of grain ethanol fuel, and is a promising cellulosic biofuel crop (Rooney et al., 2007).

S. bicolor × S. propinquum is considered to be the most distant euploid cross that could be accomplished using the cultigen (S. bicolor) by conventional and interspecific means from populations of this species, offering opportunities for genetic dissection of a wide range of traits related to plant domestication and crop productivity, some of which have begun to receive attention (Chittenden et al., 1994; Lin et al., 1995, 1999; Paterson et al., 1995; Hu et al., 2003; Feltus et al., 2006).

3.5. WILD SORGHUM — ITS POTENTIAL USE IN BREEDING

S. bicolor and S. propinquum differ in traits related to perenniality (Jang et al., 2009). Both consideration of the expansion of agriculture to supply plant biomass for fuel or chemical raw material production (Tilman et al., 2009) and strategies to rebalance food production with the conservation of ecological capital (Glover et al., 2010) place very strong emphasis on perenniality. Most genes responsible for variation in rhizome size and number in sorghum and rice — an important organ of perenniality — mapping to corresponding chromosomal locations, suggests that information on rhizomatousness from several model species can be generally extrapolated to a wide range of taxa (Hu et al., 2003).

3.6. STRATEGIES FOR MAXIMIZING THE USE OF GENETIC RESOURCES IN SORGHUM

Gene exchange has tended to be most efficient when wild species are closely related to the crop or are even direct ancestors of the domesticated species. Although historically traits are transferred from wild relatives to cultivated forms, this is often difficult due to crossing incompatibility and hybrid sterility (Stebbins, 1958; Zeven et al., 1983). However, recent technological advances have facilitated character transfer between unrelated species and extended the value of wild relatives by increasing their utility in secondary and tertiary gene bases of crops (Meilleur and Hodgkin, 2004).

Sorghum improvement has so far relied on exploiting variability within the primary gene pool, with gene transfer from one form to another being done relatively easily. S. halepense and S. propinquum, each naturally introgressive with cultivated sorghum and their wild races (Cefarier 1958; de Wet 1978), have their few wild taxa that can be used in conventional breeding programs. Even so, most sorghum improvement work has been conducted within sorghum races of the same species or closely related ones from the same section. Wild species from the other four sections fall within the tertiary gene pool, making gene transfer to domesticated forms possible.

The use of interspecific hybridization is difficult due to strong sterility barriers (Harlan and de Wet, 1971), and for this reason distant crosses with wild sorghum forms have not been successful (Duncan et al., 1991; Rosenow and Dahlberg, 2000). The main barrier to interspecific hybridization is associated with adverse pollen–pistil interaction (Sun et al., 1991; Huelgas et al., 1996; Shivanna and Seetharama, 1997; Hodnett et al., 2005) and hybridization failure (Kuhlman et al., 2008).

Nwanze et al. (1990) reported several F1 seeds obtained from an Sorghum dimidiatum (Parasorghum) × cultivated sorghum cross, with varying degrees of sterility. Cytoplasmic male-sterile plants of S. bicolor, homozygous for the iap allele, were pollinated with three divergent sorghum species, S. angustum Blake, S. nitidum (Vahl) Pers. and S. macrospermum Garber. Pollen from these three wild species germinated easily and pollen tubes grew to the base of the S. bicolor ovary within 2 hours after pollination. Hybrid embryos were detected in S. bicolor between 13 and 20 days after pollination. S. bicolor × S. angustum and S. bicolor × S. nitidum hybrids were obtained using embryo rescue followed by in vitro culture techniques, while S. bicolor × S. macrospermum hybrids were obtained through simple germination of hybrid seeds. These hybrids clearly demonstrate that the recessive iap allele bypasses pollen–pistil incompatibilities in the genus Sorghum and allows hybridization between S. bicolor and species from the tertiary gene pool.

Interspecific hybrids were obtained from crosses between Sorghum bicolor × S. macrospermum Garber, S. bicolor × S. angustum Blake, and S. bicolor × S. nitidum (Vahl) Pers., and these are of breeding interest due to their resistance to important pathogens and pests. The hybrid nature of these progeny was confirmed by the presence of genomes from both parental species, which could be easily identified based on chromosome size and number (Price et al., 2006).

The use of wild relatives in sorghum improvement is still in its early stages, but they can offer a range of valuable traits, and the recent discovery of the recessive iap allele that bypasses pollen–pistil incompatibility represents an enormous potential within the genetic base of wild sorghum.

Wild relatives of crop plants, for all their demonstrated value and evident potential, have not been fully exploited. Lack of awareness of their potential as a model of variability, reproductive biology, knowledge and skills for identification, etc., are the main difficulties associated with various improvement programs when using wild form germplasm. Nevertheless, they constitute a huge reservoir of genetic variation for improved crops and are a critical resource for supporting food security. Genes from wild plants have provided crops with resistance to numerous pests and diseases, and have improved their tolerance to extreme temperatures, salinity and drought — a value of increasing importance under climate change conditions.

Multiple genes, to impart desired characteristics and higher biological yield, are needed for the progressive improvement of cultivated sorghum. The availability of these genes depends on identifying geographical regions with a concentration of different traits with agronomic value. Identifying these sites is of paramount importance for designing appropriate sampling strategies for germplasm collection and for in situ selection, appropriate to complement ex situ conservation. In situ conservation may depend on estimated high diversity based on markers or knowledge of adaptive traits linked to certain ecological conditions (Workeye, 2002), for example, host-pathogen co-evolution systems and adaptation to other stress conditions.

Androsterility in sorghum is controlled by two mechanisms — nuclear (genic) and cytoplasmic-nuclear. Genic (nuclear) androsterility is controlled monogenically and is transmitted recessively (Karper and Stephens, 1936, cited by Butnaru et al., 1991).

Cytoplasmic androsterility (mSc1, mSca) was identified in 1952, in a cross between a Milo group genotype used as the female parent and a Kafir group genotype used as the male parent. From these crosses, an androsterile genotype resulted. The observed result of the reciprocal cross Kafir ♀ × Milo ♂ is a fertile hybrid. The appearance of the androsterility phenomenon observed in the Milo ♀ × Kafir ♂ cross is due to the interaction between Milo-type cytoplasm, which carries factors that induce androsterility, and nuclear (gene) factors from Kafir that maintain androsterility (do not restore pollen fertility). This type of cytoplasmic androsterility has been named Milo × Kafir and is used in all breeding programs (Antohe et al., 2006).

Heterosis in sorghum influences grain production (reproductive heterosis), vegetative mass production (somatic heterosis), and adaptation to unfavorable environmental conditions (adaptive heterosis). Plant height, length of the growing period, degree of tillering, and number of grains per panicle are most strongly influenced by the heterosis effect.

Heterosis manifests positively dominant for panicle size, number and size of leaves, number of grains, grain size, and negatively for traits such as rhizome type, perenniality, and some quality characteristics. The most pronounced heterosis has been observed between milo and hegari varieties, between feterita and caudatum, and between dochna (sweet sorghum) varieties and broom sorghum (Antohe et al., 2006).

Mutation — Natural mutations have played an important role in the emergence of various sorghum types, particularly dwarf types. Studies published by Antohe et al. (2006) show that dwarf milo forms derived from normal forms as a result of the mutation Dw1→dw1, while double-dwarf forms arose through mutation of gene Dw2→dw2.

Through back-mutation (reversion) dw3→Dw3 and dw4→Dw4, height increases. Back-mutations occur at a rate of 4:1,200. Natural mutations occur at high frequency and with special benefit, making it possible to identify characters of interest such as earliness, short internodes, disease resistance, and androsterility.

Research by Celarier (1956), Endrizzi (1957) and Hadley (1953) indicates polyploidy relationships between sorghum species. Autopolyploids of the Hegari grain sorghum variety (n=10) were obtained using colchicine (Chin, 1946). Both tetraploid (2n=40) and octoploid (8n=80) forms were observed. Polyploid forms were shorter, more vigorous, but later-maturing than the diploid counterpart. Tetraploid forms produced sterile pollen at 18%, while octoploids produced 80% sterile pollen (Antohe et al., 2006).

CHAPTER IV

MORPHOLOGY OF SORGHUM

(Authors: Matei Gh., Popa L.D.)

Sorghum is a C4 metabolism plant with high photosynthetic efficiency, which can be cultivated under very difficult conditions, from arid to semi-humid areas.

For forms with naked grain, sorghum exhibits unipolar germination, with the coleoptile colorless or slightly violet, and produces a single embryonic root during germination (Figs. 4.1 and 4.2). Forms with caryopses partially enclosed in glumes, in which germination is bipolar, are also mentioned in the literature.

Sorghum develops a well-developed root system with numerous absorbing root hairs that provide very good drought resistance. Initially, like maize, it develops a temporary root system comprising the primary root and adventitious roots emerging from the first subterranean node. The activity of these roots lasts a short time, ensuring the plant's nutrient and water requirements until the permanent root system forms.

The permanent root system of sorghum begins forming from the second subterranean node and continues developing throughout the entire growing period.

A particular characteristic of sorghum's root system is that active root growth continues even after the plants have reached maturity (due to perenniality traits inherited from wild forms), allowing the plant to regenerate after successive mowing, grazing, or destruction of aboveground mass by radical weather phenomena such as hail (Antohe et al., 2006, 2007).

Permanent roots penetrate deep into the soil — to 150–200 cm — while the bulk of the root mass reaches 90 cm. From aboveground stem nodes, brace roots emerge, similar to maize

(Fig. 4.3). In drought years, these aerial adventitious roots develop poorly and remain as nodules (Pochiscanu et al., 2016).

Sorghum plants have a fibrous root system that can reach a depth of up to 1.5–2.4 m (Kimber, 2000). An extensive root system and the ability to become active during water stress contribute to sorghum's drought resistance, making it a drought-tolerant crop (Whiteman & Wilson, 1965).

Sorghum roots develop laterally and can extend to 90 or even 150 cm. Compared to the maize root system, sorghum possesses twice as many secondary roots at any stage of development, which explains its greater resistance to thermal and water stress factors.

Wall and Ross (1970), as cited by Antohe (2007), note that these permanent roots develop continuously, except during periods of severe drought, but resume growth immediately when conditions become favorable again, producing "new rain roots" whose function helps the plant resume vegetative growth or continue the generative stage.

According to the same cited authors, root system formation and development occurs in whorls; approximately 8 such units typically form, from which adventitious roots develop. They form gradually as the plant progresses through its developmental phenophases, reaching 6–7 whorls formed near ear emergence, and whorls 7 and 8 appearing at flowering and fertilization.

THE STEM is straight, erect, 1–4.5 m tall, capable of reaching 6.5 m under highly favorable conditions.

Internally, the stem is filled with dense, dry or juicy pith. This rich medullary tissue has a high water storage capacity, and during the growing period, significant amounts of carbohydrates are deposited in it (75.37% of dry matter, compared to 72.48% in maize stem) (Muresan, 1965, cited by Antohe et al., 1991). Given that these can have different percentages of succulence, the most valuable forms are considered those where the amount of juice is more than 30%.

Sorghum has a stem consisting of 7–20 internodes, whose length increases from the base toward the top, with values between 12–14 cm and even 25 cm. Stem diameter in sorghum varies between 0.6–4 cm.

The growth rate of the sorghum stem is very slow in the early vegetative stages (when the root system develops predominantly) and accelerates after the plant has formed 5–7 leaves.

In sweet sorghum, carbohydrate content differs along the stem length, with the highest concentration observed in the lower half of the stem.

Sorghum has a strong tillering capacity — an undesirable trait in grain sorghum but favorable in forage or sweet sorghum (Fig. 4.4).

Tillers or ratoons (shoots) form from the first node at the soil surface. The number of tillers formed per plant is strongly influenced by the cultivar or hybrid grown, the applied technology, and climatic conditions during the growing season.

Sorghum tillers more vigorously when cultivated at lower densities under conditions of high moisture and fertility. Each stem contains nodes that can produce new tillers if the upper part of the stem is damaged. The lowest nodes on the stem contain buds that can give rise to lateral shoots, while basal tillers will form at the first node (House 1985; Doggett 1988).

Stem tillering in sorghum begins at the 5–7 leaf stage. Under optimal conditions, a single plant can form 2–10 tillers that, depending on climatic conditions, can set seed and reach maturity.

Stem elongation in the first 30 days of vegetative growth is very slow, and therefore the plant can easily be smothered by weeds (Matei, 2013).

TABLE 4.1 — Morphological characteristics (3-year average) of a range of sweet sorghum hybrids tested in three different areas: southern Oltenia (SCDCPN Dabuleni, irrigated),

central Moldova (SCDA Secuieni, non-irrigated), and Caracal Plain (SCDA Caracal, non-irrigated), average 2018–2020:

- ISASM 1: plant height 314/305/315 cm; stem diameter 214/169/208 mm
- ISASM 2: plant height 292/271/296 cm; stem diameter 203/153/201 mm
- IES ATHENA: plant height 248 cm; stem diameter 177/—/228 mm
- IBMR GOLD: plant height 255/—/— cm; stem diameter —/228/191 mm
- SUPERSILE 20: plant height 254/288/— cm; stem diameter 186/175/— mm
- AVERAGE: plant height 268/280/272 cm; stem diameter 195/—/194 mm

LEAVES of sorghum resemble those of maize; in very young plants they are glabrous (a character that distinguishes them from maize). They are alternately arranged, with a well-developed sheath covering 2/3 of the internode, with a long leaf blade (40–100 cm), 5–12 cm wide, and a prominent midrib that is lighter in color than the rest of the blade (Feher, 2010; Matei, 2010).

The midrib also provides mechanical support for the leaf blade and can take different forms: flattened or prominently raised; concave on the upper surface and convex on the lower surface. It can serve as an indicator of pest or pathogen attack, as it pigments red as a sign of plant disease.

At the basal portion of the upper surface of the leaf blade there are long, soft hairs; the rest of the blade surface is glabrous and waxy. The ligule is hairy, short and truncate; auricles are absent.

The main characteristic of sorghum leaves is that they are waxy, having a thick cuticle with the ability to close stomata during hot weather, thereby reducing evapotranspiration — a physiological mechanism conferring greater resistance than maize to thermal and water stress. Stomata size in sorghum leaves is estimated at about 2/3 of those of maize, but their number is 50% higher than in maize.

Clark (1970) showed that different sorghum varieties form 4 leaves from the embryo. Additional leaves appear after sowing until floral initiation, which is controlled by four maturity genes (Quinby, 1972; Quinby, Hesketh and Voigt, 1973). This period was found to last approximately 30 days, regardless of variety (Pauli, Stickler and Lawless, 1964).

It has been shown that the number of sorghum leaves decreases under water stress conditions. Bennett (1975) reported a reduced number of leaves for sorghum under water stress. Similarly, Vinall and Reed (1918) concluded that lack of water was partly responsible for the reduction in leaf number. Sieglinger (1936) concluded that the number of leaves decreases if sowing is delayed.

Research by Ma (2004) showed that under drought conditions, leaves fold upward and inward, reducing transpiration and water loss by decreasing the exposed surface area.

Doggett (1988) noted that wax deposits were found in leaves — a feature related to drought tolerance. Wax deposited on the leaf surface acts as a physical barrier that mitigates water stress, reduces transpiration and prevents pest penetration into plant tissues (Ma, 2004).

Leaf color is generally lighter than that of maize, especially in the early vegetative stages, but is also influenced by cultivation conditions and the level and nature of nutrients accessible to the plant.

In sweet sorghum, where carbohydrate accumulation in the stem is higher, leaves have a midrib colored gray or grayish. In forms poorer in carbohydrates, this midrib color is white.

THE INFLORESCENCE is a panicle 20–40 cm long, with forms varying by branch length; in the broom sorghum variety (var. technicum) it can reach 100 cm. Panicles can be loose (effusum type) or compact (contractum type) (Figs. 4.5 and 4.6).

A panicle contains between 1,000 and 5,000 flowers arranged in spikelets grouped in pairs or triplets, of which only the median-positioned sessile spikelet is fertile (Pop and Suveti, 1998).

The sessile spikelet is lanceolate, slightly flattened in the median zone, with variable color from white, straw yellow to cream, red or dark: purple, brown or nearly black.

Glumes are convex and may cover the seed to varying proportions: 1/3, 2/3 or completely. Awns may be persistent or caducous at maturity. Like most cereals, sorghum has three stamens and, as a particular feature, two pistils (Antohe, 2006).

Flowering begins 2–3 days after panicle emergence and lasts 5–10 days (Salontai, 1982), proceeding from the tip toward the base of the panicle. Mature pollen germinates only in light.

Pollination is predominantly autogamous and occurs in the early morning hours. Cross-pollination (allogamy) in sorghum is still very frequent, being accentuated by hot weather, high light intensity, soil water deficit and low air humidity.

Flower opening generally occurs early in the morning or at night. Ripening uniformity is greater in tighter, more compact panicles than in loose ones.

Eastin (1968) observed that sorghum panicles intercept 40–48% of total solar radiation from 9 AM to 3 PM.

In another study, Eastin and Sullivan (1969) reported that loose sorghum panicles had greater weight at all growth stages compared to compact type panicles. They attributed this difference to the higher rate of photosynthesis occurring in looser panicles due to better light penetration.

Research by Fischer et al. (1976) showed that the average contribution of the inflorescence to total biomass yield is 13%.

THE FRUIT is a caryopsis enclosed in glumes or naked, globular, ovoid, slightly laterally compressed, white, pink, reddish or gray in color (Fig. 4.7).

Sorghum seeds are small, with a variable thousand-grain weight (TGW): small 8–10 g, medium 12–24 g, or large 25–45 g. Hectoliter mass falls between 65–75 kg/hl.

The caryopsis is composed of pericarp (7.3–9.3%), endosperm (80.0–84.6%) and embryo (7.8–12.1%).

Under the pericarp, in some forms, there is a cell layer — the testa — containing tannin, which confers high resistance to pathogen attack, insects and even birds and herbivorous species.

CHAPTER V

CHEMICAL COMPOSITION OF SORGHUM

5.1. BIOCHEMICAL COMPOSITION OF GRAIN SORGHUM

(Authors: Croitoru M., Dima M., Matei Gh., Apostol L., Vrinceanu N.)

Determining the quality of sorghum grain is an objective that must be pursued with the same persistence as production capacity. Establishing grain quality allows both diversification and enhancement of the economic value of sorghum cultivation. Knowledge of grain quality is important in association with achieving grain production and other agronomic characteristics, but also for improving nutritional and industrial properties.

Studies show that sorghum can completely replace animal feed with nutritional qualities equal to or greater than those of maize. Sorghum digestibility is approximately 86% of dry matter. It has a higher protein level compared to maize. Starch and fat content of sorghum is similar to that of maize.

Moreover, the advantage of sorghum lies in its high protein content. Digestible energy of sorghum is quite high — approximately 86% of dry matter (DM) — as is protein and amino acid digestibility. The flexibility offered by sorghum in recipe formulation allows the nutritionist to reduce costs while maintaining the same growth rate.

The fat content of sorghum is similar to that of maize, but with a better fatty acid profile. Fat substances in sorghum contain fewer unsaturated fats.

The qualitative advantage of sorghum over maize was confirmed by several researchers in the Maize and Sorghum Survey in France — ARVALIS/FranceAgriMer 2009–2013 (Table 5.1), updated with values from INRA-AFZ 2004 tables.

TABLE 5.1 — Biochemical Composition of Sorghum and Maize Grains (ARVALIS/FranceAgriMer 2009–2013, updated with INRA-AFZ 2004):

Composition | Sorghum (%) | Maize (%)

Starch: 75.1 / 75.8

Proteins: 10.6 / 8.7

Fats: 4.4 / 4.5

Cellulose: 8.3 / 9.3

Sugars: 0.8 / 1.9

Calcium: 0.04 / 0.05

Phosphorus: 0.32 / 0.30

Lysine: 0.25 / 0.28

Threonine: 0.36 / 0.35

Methionine + Cysteine: 0.38 / 0.43

Tryptophan: 0.12 / 0.06

From total world sorghum production, consumption breaks down as follows: 53.3% for human food, 39.4% for animal feed and 2% in the food and light industry (Nica, 2011).

Sorghum forms a major source of protein and calories in population diets. Like other vegetable proteins, its protein is of poor quality. Inadequate consumption of dietary proteins is an important factor responsible for the widespread prevalence of protein-calorie malnutrition observed in vulnerable population segments such as growing children and breastfeeding mothers. A public health concern regarding a high incidence of pellagra is observed among sorghum consumers (Gopalan & Srikantia, 1960). Thus, the nutritional quality of sorghum is an important aspect of the sorghum improvement program (Salunkhe et al., 1977).

Sorghum is a cereal rich in nutrients, dietary fiber and bioactive components, but considered of low value for humans and often used as animal feed.

The USA is a major sorghum producer, but the grains are not consumed as human food — except for a very small fraction — and are used as animal feed; in Africa and India, however, grains form the basic diet for the population, where all products are used directly as human food.

Sorghum, like other cereals, is an excellent source of starch and proteins. It is a gluten-free cereal, which has significance in the current scenario where the occurrence of celiac disease (CD) — an immunological response to gluten intolerance — is increasing. Sorghum contains phenolic compounds such as flavonoids (Shahidi & Naczk, 1995) which have been shown to inhibit tumor development (Huang & Ferraro, 1992). Starch and sugars from sorghum are released more slowly than from other cereals (Klopfenstein & Hoseney, 1995) and therefore could be beneficial for diabetics (Toomey, 1988).

The main carbohydrate storage source in sorghum grain is starch, similar to other cereals; the average starch content is 69.5% (Jambunathan & Subramanian, 1987). Sorghum has similar starch quantities to wheat flour, but with significantly lower α-amylase activity (40–

50%) and amylolytic activity of only 10% compared to wheat flour (Zhumabekova et al., 1978).

Sorghum has a higher crude fat content (3%) than wheat or rice. Germ and aleurone layers are the main sources of fat content. The germ contributes approximately 80% of total fat (Rooney et al., 1991). The mineral composition of sorghum grain (Table 5.2) is highly variable. The concentration of mineral elements in sorghum grain varies due to genotypic and environmental influences and genotype × environment interactions.

TABLE 5.2 — Mineral Composition of Sorghum Grain (Gerrano et al., 2015) [mg/kg dry matter]:

- Ca: 270.37
- Fe: 38.92
- K: 1,384.41
- Mn: 15.05
- Na: 23.59
- P: 2,692.19
- Zn: 17.80
- Mg: 1,184.67

Sorghum is a rich source of B complex vitamins. Other fat-soluble vitamins — D, E and K — have also been found in sorghum grain. Sorghum is not a source of vitamin C. The concentrations of thiamine, riboflavin and niacin in sorghum are comparable to those in maize grain (Table 5.3) (Oluwafemi Ayodeji Adebo, 2020).

TABLE 5.3 — Vitamin Content (mg/100 g) of Sorghum Grain (Oluwafemi Ayodeji Adebo, 2020):

- B1 (Thiamine): 0.34–0.73 (across sources)
- B2 (Riboflavin): 0.12–0.16
- B3 (Niacin): 2.99–4.88
- B5 (Pantothenic acid): 1.55–1.63
- B6 (Pyridoxine): 0.17–0.59
- Folic acid: 0.02

Cellulose is a major component of sorghum insoluble fiber and can present values between 1.19% and 5.23% in sorghum grain (Kamath & Belavady, 1980). Grain sorghum also contains phenolic compounds other than tannin that affect sensory and nutritional quality (Hahn et al., 1980).

Determinations regarding grain quality characteristics of sorghum have been the subject of much research that has highlighted the influence of variety, technological factors and climatic factors on protein, fat, moisture, cellulose, tannin content, etc. (Bean et al., 1984; Khalil et al., 1984; Basahy, 1995; Rooney & Serna-Saldivar, 2000; Gassem & Osman, 2003; Abdel-Rahman, 2000; Antohe, 2007; Nica, 2011; Pochiscanu, 2016; Mabelebele et al., 2015).

In Romania, research has focused on determining the production potential of grain sorghum hybrids (Sorghum bicolor (L.) Moench var. eusorghum) under restrictive pedoclimatic conditions (Muresan, 1961; Antohe, 2002; Draghici, 2007; Matei, 2011), with results varying under the influence of factors [continued...]

The climatic evolution toward warming and aridification in the 2001–2050 period in the Balkan zone, which includes Romania, necessitates reconsidering sorghum as a food cereal (grains used in composite flour formulations destined for glutenous and gluten-free bakery products).

Croitoru et al. (2018) showed that under the conditions of sandy soils in southern Oltenia, the protein content of grains presented different values depending on the hybrid under study and the climatic conditions of the cultivation zone. The average protein content in sorghum grain ranged from 13.8% (hybrid Shamal) to 20.5% (hybrid Es Mousson), with a hybrid average of 17.22%. Protein content above the hybrid average was determined in hybrids Elan (19.2%), Es Alize (18.3%), Aloanus (17.6%) and Armonik (17.5%).

Similar results were obtained by Khalil et al. (1984) for sorghum hybrids in Saudi Arabian conditions (15.3–15.9%); research by Mabelebele et al. (2015) indicated much lower protein content values (8.1–9.5%), similar to those of Rooney & Serna-Saldivar (2000) who reported crude protein content in sorghum grain between 6.0 and 10.0%.

Njuguna et al. (2018) showed that crude protein content varies between 8.9% and 15.4% depending on the study zone, indicating that the growth environment affected the nutritional content of sorghum lines differently.

Within Project No. 9/PCCDI/2018 "Complex System for the Integral Valorization of Agricultural Species with Energy and Food Potential," valuable results were obtained on the chemical composition of 8 sorghum hybrids cultivated in different zones: SCDA Caracal (Oltenia Plain) and SCDA Secuieni (Central Moldova). Analysis of sorghum seed flour showed that sorghum contains substances with functional potential — dietary fiber and minerals.

TABLE 5.4 — Average Physico-Chemical Composition of Sorghum Hybrid Seeds (Internal Report Apostol L. — IBA Bucharest, 2018) [% dry matter]:

- Kalatur: Protein 11.54 / Fat 3.75 / Crude fiber 2.55 / Starch 68.01
- Shamal: 9.46 / 4.16 / 2.60 / 67.16
- Alimentar: 12.05 / 3.72 / 2.65 / 68.27
- Elan: 12.21 / 3.74 / 2.49 / 67.70
- Albanus: 11.37 / 2.23 / 3.07 / 67.27
- Arsky: 11.12 / 3.42 / 2.35 / 69.88
- Es Foehn: 10.13 / 3.93 / 2.53 / 67.79
- Armorik: 11.14 / 3.88 / 2.85 / 70.87

The high starch content of the analyzed sorghum seeds is an advantage for their use in animal feed as a maize substitute. Sorghum flour can also be successfully used in the food industry as a wheat flour substitute, especially in gluten-free bakery products.

TABLE 5.5 — Average Mineral Content of Seeds of Sorghum Hybrids (2018 harvest) [mg/100g DM]:

Hybrid | P | K | Ca | Mg | Fe | Zn | Cu | Mn

Kalatur: 290/510/23/275/144/20.56/2.97/14.29

Shamal: 205/590/32.5/270/189/22.03/2.97/17.31

Alimentar: 310/550/28.5/285/150.5/20.38/2.57/16.01

Elan: 320/510/31/275/123.5/19.36/2.04/16.60

Albanus: 320/500/23.5/285/110/21.07/3.03/15.70

Arsky: 280/620/26.5/260/141/19.12/2.79/14.43

Es Foehn: 315/490/22/275/129/21.30/2.38/17.15

Armorik: 315/515/—/275/—/—/—/—

The sorghum seed samples have a high iron content in their composition, thus qualifying for the designation "source of iron" (EU Regulation No. 1924/2006; Directive 90/496/EEC). The samples also have a significant magnesium and zinc content (more than half of the daily dose, FDA-2011).

TABLE 5.6 — Amino Acid Content of Sorghum Protein in Sorghum Hybrids (2018 harvest) [% of protein]:

Predominant constituent amino acids: Glutamic acid (21.73–19.57%), Leucine (13.58–12.95%), Proline (9.16–8.35%), Alanine (9.21–7.79%), Aspartic acid (6.65–5.29%).

TABLE 5.7 — Chemical Score of Essential Amino Acids of Sorghum Protein (2018 harvest, vs. FAO/WHO/UNU reference):

- Leucine: FAO reference 2.80 g/100g protein; sorghum 3.75; score 133.93%
- Isoleucine: 6.60/12.98/198.69%
- Alanine: 6.30/4.81/76.39%
- Valine: 7.90/2.15/111.84% [Note: apparent OCR error in original]
- Histidine: 3.50/4.96/141.79%
- Threonine: 3.40/3.03/88.97%
- Methionine: 2.20/1.70/77.27%

From this analysis it can be concluded that these amino acids are at concentrations exceeding the recommended daily intake (FAO/WHO/UNU). Lysine is the most limiting essential amino acid.

Importance of essential amino acids found in sorghum seeds for the human organism:

- Leucine contributes to normalizing nitrogen balance and protein/carbohydrate metabolism. Leucine deficiency in animals slows growth, reduces body mass, and causes modifications at the level of the liver and thyroid gland.
- Valine: Deficiency in the diet causes coordination disorders and hypertension.
- Isoleucine is a component of body proteins. Deficiency causes nitrogen imbalance in the organism.
- Histidine participates in hemoglobin synthesis. Decarboxylation of histidine contributes to histamine formation, which dilates blood vessels and increases wall permeability.
- Threonine is vital for health and cannot be synthesized by the organism. It is found in significant quantities in the central nervous system and is useful in treating various types of depression. It has an important role in maintaining skin and joints, participating in the synthesis of glycine and serine — amino acids that help synthesize collagen and elastin. It has a role in proper fat metabolism, together with methionine and aspartic acid, in certain organs — especially the liver — preventing fat accumulation and helping maintain appropriate protein levels in the organism.
- Methionine is the principal donor of labile methyl groups used in choline synthesis (a substance with active biological properties and lipotropic action). Methionine normalizes lipid and phospholipid metabolism in the liver and is recommended in the prophylaxis and treatment of atherosclerosis.
- Phenylalanine participates in normalizing thyroid and adrenal gland function. Tyrosine — which contributes to adrenaline formation — is synthesized from phenylalanine.

Fat content results (Mabelebele et al., 2015): values between 2.7% and 3.7%. Under favorable moisture conditions, sorghum responds well to nitrogen fertilization both in terms of yield level and protein content. In drought zones, phosphorus also has a favorable effect. Fertilization rates currently practiced worldwide vary between N50-150 P36-100, depending on experimental conditions. Under irrigated conditions, Giardini (1981), cited by Bilteanu (1998), recommends N200P150.

5.2. BIOCHEMICAL COMPOSITION OF SWEET SORGHUM

(Authors: Croitoru M., Dima M.)

Sweet sorghum (Sorghum bicolor (L.) Moench) is an important plant for animal feed and human nutrition. It is the only crop that offers both grain and stalks that can be used for sugar, alcohol, syrup, forage and fuel. The juice of a good sweet sorghum variety, grown under appropriate conditions, contains 13 to 17% sugar, of which 10 to 14% is sucrose (Martin et al., 1976).

Sweet sorghum is harvested for syrup extraction beginning from the milk grain ripening stage and may continue until full ripeness. Harvesting can be done by cutting whole plants, after which the last internode — low in sugar but rich in mineral salts — and leaves are removed; the stalks are bound in bundles and transported to pressing stations.

The syrup extracted from sweet sorghum stalks has a balanced nutritional profile containing proteins, essential amino acids and minerals (FAO, 1994). One tablespoon (20g) of sorghum syrup contains 62 calories and 15 g of carbohydrates. Sweet sorghum contains hard-to-find nutrients such as iron, calcium and potassium. Pure syrups contain no protein or fat. Sweet sorghum syrup has high antioxidant activity — found to be four times the antioxidant power of the most natural honey tested (Kulkarni et al., 2018).

Sweet sorghum leaves are characterized by protein content (% DM) in the range of 6.70–7.30% and sugar 2.22–2.91% (Bahcivanji et al., 2010). Starch content in leaves was 4.2%, ash 11.0%, crude fat 3.30% and crude cellulose 23.6%.

During the growing season, the chemical composition of sweet sorghum stalks undergoes changes: total sugar increases from milk ripeness toward physiological maturity, while crude cellulose and crude protein decrease toward physiological maturity.

TABLE 5.8 — Chemical Composition of Sweet Sorghum Stalks Harvested at Different Grain Maturity Stages (Fundulea, 1983–1999):

Hybrid/variety | Total sugar (%) | Cellulose (%) | Crude protein % (N×6.25)

At MILK MATURITY:

- F.215-86: 14.3 / 29.3 / 11.3
- Roza 1: 19.2 / 30.5 / 8.4
- F.463-87: 25.6 / 31.1 / 9.3
- F.450-4/86: 16.3 / 29.70 / 10.4

At WAX MATURITY:

- F.215-86: 53.5 / 26.3 / 6.2
- Roza: 56.5 / 23.4 / 6.8
- F.463-87: 53.4 / 25.5 / 7.7
- F.450-4/86: 37.4 / 23.0 / 5.8

At PHYSIOLOGICAL MATURITY:

- F.215-86: 58.2 / 26.2 / 5.3
- Roza: 60.2 / 25.2 / 7.1
- F.463-87: 61.7 / 26.1 / 6.0
- F.450-4/86: 63.6 / 24.3 / 6.6

The sweet sorghum juice has a chemical composition of: sucrose 10.9–14.7%, glucose 2.53–3.14%, fructose 1.08–2.19% (Antohe, 2007). Total nitrogen is present at an average concentration of 0.26–0.51%; potassium 377.6 mg/100g DM; Ca 8.29 mg/100g DM; Mg 19.68 mg/100g DM; Na 3.6%; Fe 2.61%. The juice has an average pH of 4.5–5.4, an average density of 1.066 g/cm^3 and an average Brix value of 15.7–24.3%.

Sweet sorghum grain contains average protein: 11.4% (Carmen), 12.5% (F.135 ST) to 14.2% (F.351 hl); average starch 65% (Carmen), 74% (Doina); oil content 3.2% (Roza), 4.2% (F.351 hl); lysine 0.20–0.56 g/100g DM; tryptophan 0.105–0.115 g/100g DM; tannin 0.28% (Doina) to 0.53% (F.135 ST) (Antohe, 2007).

For direct fertilization of sweet sorghum targeting juice quality, cultivation on fertile soils is recommended for food purposes. When the juice is used for purposes other than food, fertilization can be applied with N90-120, P_2O_5 70-80.

In a study in Missouri on different nitrogen fertilization rates, Holou & Gene (2012) showed that the sugar content (Brix degrees) of the juice varied between 10.7% and 18.9%. Nitrogen fertilization improved juice sugar content. There was a negative correlation between sugar concentration and juice yield. The highest values of total soluble solids concentration (14.89%), sugar content in juice (22.91 g), sugar concentration in juice (527.46 mg g^{-1} DW), dry biomass percentage (60.04%) and dry biomass yield (19.01 t ha^{-1}) were observed at the physiological maturity stage of the plant (Iovany Lopez-Sandin et al., 2021).

Smith et al. (1987) evaluated six sweet sorghum hybrids over 4 years for fermentable sugar production potential at eight locations in the continental USA and one in Hawaii. Stalk sugar content (Brix degrees) ranged from 10.5% to 20.7%, and ethanol content ranged from 4,152 L/ha to 9,157 L/ha.

Ekefre et al. (2017) determined ethanol production between 5,077 L/ha and 7,619 L/ha.

Sweet sorghum is cultivated for the large amount of soluble sugars (a mixture of sucrose, glucose and fructose) contained in its tall, succulent stalks (Smith et al., 1987; Murray et al., 2009). Historically, sweet sorghum was grown to support syrup and molasses production, but there is growing interest in its use as a raw material for renewable fuels and chemicals (Calviño & Messing, 2012; Vermerris & Saballos, 2013). Plants have been found to exceed 3 meters in height and can produce fresh biomass yields of 45–112 Mg ha^{-1} (20–50 tonnes/acre), depending on genotype and location (Erickson et al., 2012).

Numerous studies have demonstrated a positive correlation between plant height and sugar accumulation. Since the physiological mechanisms underlying sugar accumulation in sweet sorghum are not well understood, it is not known whether the apparent association between stalk sugar accumulation and plant height is the result of selection or dictated by physiological or genetic constraints. Research by Sanyukta Shukla et al. (2017) showed that increased sugar concentration in sweet sorghum is not conditioned by plant height, making it feasible to develop shorter, high-sugar lines.

Chlorophyll level indicates the photosynthetic activity of the plant and can be used to determine the maturity and harvesting stage of sweet sorghum. High chlorophyll content in leaves is linked to high photosynthetic activity, and remote sensing chlorophyll content detection can indicate the appropriate harvesting stage for alcohol production.

5.3. BIOCHEMICAL COMPOSITION OF SORGHUM × SUDANGRASS HYBRIDS

(Authors: Croitoru M., Dima M.)

The chemical composition of the components of the green mass (leaves, stems, panicles) of sorghum × sudangrass is differentiated by plant organ. Protein content in leaves is between 1.1 and 3.2% depending on the hybrid studied, and in stems between 0.5 and 1.1%. Protein content in panicles is on average 1.1%. Cellulose content was highest in leaves, reaching up to 18% (Antohe, 2007). Nitrate content was lowest in panicles and highest in stems, up to 99 mg/100g DM.

Hydrocyanic acid concentration, determined at 28 and 30 days after mowing, is low and permits grazing by cattle and sheep, both when harvested at the early boot stage and at milk maturity. At 4–5 days after frost, both green and dry leaves can be fed to cattle without poisoning risk, as the HCN concentration determined is low (below 50 mg HCN/100g DM) (Antohe, 2007).

5.4. BIOCHEMICAL COMPOSITION OF BROOM SORGHUM

(Authors: Croitoru M., Dima M.)

Broom sorghum is cultivated generally for panicles with straw-yellow colored branches, both for domestic use and for export to Europe, which leads to harvesting at physiological maturity or complete grain maturity, resulting in a single cut by which both panicles (without grain) destined for brush/broom making and grains usable as animal feed or for ethanol production are valorized (Antohe, 2007).

[NOTE: Pages 98–105 of Volume 1 contain the bibliography of Chapter V and the beginning of Chapter VI (Importance of the species). The remaining chapters of the monograph continue in Volumes 2–4.]

[TRANSLATION CONTINUES IN VOLUME 2 FILE]

SORGHUM — INNOVATIVE TECHNOLOGIES FOR CULTIVATION AND VALORIZATION

VOLUME 2: Pages 106–227

CHAPTER VI

IMPORTANCE OF THE SPECIES

(Authors: Iancu P., Matei Gh.)

Sorghum is cultivated worldwide on extensive areas in India, China, the USA, Argentina and some African countries. The area in the European Union ranges between 420,000–460,000 ha, with France and Italy as the main growers (EUROSTAT, 2018).

In Romania, sorghum cultivation has expanded significantly in recent years, due to its adaptability to semi-arid zones, soils with low fertility, drought resistance and reduced production costs compared to maize cultivation. In Romania, average sorghum production in the period 2013–2017 was 42,358 tonnes, and in 2017 the recorded sorghum production was 54,280 tonnes (FAOSTAT, 2019).

Sorghum cultivation expanded very rapidly after 1950, with the creation of high-productivity hybrids and the possibility of harvesting with grain combines. By expanding onto alkaline soils less favorable for maize, the sorghum seed area could increase. Because it tolerates high temperatures during the growing season, sorghum could be a solution for arid zones in Romania.

Sorghum plants prefer areas with warm climates, such as the plains of southern Muntenia and Oltenia, the Banat Plain and the Central Moldavian Plain, having, for the most part, the same distribution area as maize, with which it resembles in many respects but demonstrates a higher degree of benefits.

Among the uses of sorghum:

- Food cereal (grain used in composite flour formulations for glutenous and gluten-free bakery products; sweet juice extracted from stalks for syrup, vinegar and other food products)
- Forage plant (as green mass, hay, silage)
- Industrial plant (sweet sorghum and broom sorghum destined for raw material production for the energy industry, liquid/solid/gaseous fuels, electrical and thermal energy)
- Chemical industry (paper and textile cellulose, plastic materials)
- Construction materials industry
- Handicraft industry (household and industrial brushes, brooms, wicker work)

Research in the field of plant production has evolved, and new sorghum varieties have been created that represent an excellent source of protein and energy for poultry with nutritional value approximately 95% comparable to that of maize. A very important advantage is that sorghum presents a reduced risk of mycotoxin contamination compared to maize.

Sorghum bicolor (synonym Sorghum vulgare) is a plant of the family Poaceae that can grow up to 3 m, with a pith-filled stem consisting of 9 to 15 internodes, broad and long leaves similar to maize, and panicle inflorescences with branches of varying length depending on variety. A panicle contains over 1,500 flowers.

Sorghum's root system has an extraordinary capacity for soil enrichment. From 1 ha of sweet sorghum, up to 18 tonnes of dry root mass remain in the soil. Adding the carbon found in the roots to phosphorus, potassium and other elements, approximately 3–4 tonnes of humus per hectare are produced annually upon decomposition. By comparison, most field crops do not have a positive humus balance, while orchards and vineyards are on the minus — destroying approximately 2 tonnes of humus each year.

Sweet sorghum is a leader in CO_2 absorption from the atmosphere. Deciduous forests absorb three times less carbon dioxide, and cereals absorb about ten times less. One hectare of sweet sorghum absorbs 50–55 tonnes of carbon dioxide annually, releasing vast quantities of oxygen (Cernei, 2008).

In the USA, sorghum is used as green manure or as cover crops to suppress nursery weeds through the allelopathic action of its root exudate — a mixture of hydrophobic biologically active substances called "sorgoleone."

The crop is also very useful for renewing exhausted soil. Sorghum is an excellent antioxidant and eliminates all toxic substances from soil formed on land used by industrial enterprises. The plant is widely used in crop rotation, as it removes salts from soil and exerts a phytoremedial effect.

6.1. IN HUMAN NUTRITION

In many parts of the world, sorghum has traditionally been used in various foods such as porridge, unleavened bread, cakes, couscous and various non-alcoholic and alcoholic beverages. Sorghum has unique properties that make it very suitable for food use.

Sorghum has varied uses similar to maize. Grains are used directly for human food in some areas of Africa, Asia and India. Hundreds of millions of people consume sorghum bread. It is also used as a raw material for starch and spirit extraction. From sweet sorghum stalks, a syrup with 55–60% sugar is extracted, used in confectionery and the alcohol industry (beer).

From 1 ha of sorghum, 80–100 tonnes of green mass biomass can result, from which 4.5–6 tonnes of sweetening substances expressed as sugar can be extracted. In comparison with sugar — composed only of sucrose (a not-too-healthy product) — the food juice from sweet sorghum contains only 50% sucrose, plus approximately 25% fructose and glucose each, essential and non-essential amino acids, polyphenolic substances, macro and microelements, vitamins, constituting a precious nutritional complex. Moreover, this juice from sweet sorghum stalks has a high carbohydrate content: 12–18%. From food juice, a range of derived products, beverages and blended nectars can be obtained.

Sorghum bicolor (L.) Moench is rich in nutrient content. Adding it to various dishes and baked goods can increase the protein, iron, B vitamins and dietary fiber content of foods. Sorghum flour is also rich in antioxidants such as phenolic compounds and anthocyanins, which help reduce inflammation and reduce free radicals.

Sorghum-derived products are ecological and dietary for humans, rich in vitamins and microelements, reduce cholesterol, eliminate toxins from the organism, regulate blood pressure, which substantially decreases the risk of cardiovascular diseases.

Sorghum is one of the best sources of dietary fiber. Fibers are vital for optimal functioning of the digestive system. They keep the digestive tract active and prevent constipation. At the same time, they regulate blood sugar levels, reduce cholesterol and prevent conditions such as diverticulitis, hemorrhoids, gallstones and kidney stones.

There are more than 30 different species of sorghum originating from tropical and subtropical climate regions. Most are used as animal feed or processed for alcohol or sorghum syrup production. Few are cultivated for human consumption.

In human nutrition, sorghum distinguishes itself by the absence of gluten. It thus becomes a solution for diversifying the diet of those suffering from celiac disease, increasingly numerous in recent years. Sorghum flour is rich in proteins, fiber, antioxidants and iron. It is used for making bread, biscuits, cakes or other baked products. More recently, sorghum popcorn has also been produced. Sorghum pasta has become a relatively common product in Italy and Spain. Alcoholic beverages are also produced from sorghum. Baijiu is a type of traditional spirit in China, originally made from sorghum. In Spain, the beer brands "O de Mila" and "La Gaia" use sorghum instead of barley as an ingredient.

Sorghum is an excellent substitute for wheat flour — an excellent baking ingredient for people with gluten intolerance. While protein gluten can cause digestive and other health problems in many people (bloating, diarrhea, constipation, fatigue, headaches and other symptoms), sorghum flour does not contain this protein, being easier to digest and tolerated by the organism.

In addition to avoiding gluten, there is another major benefit in using sorghum flour over wheat flour and some gluten-free blends: there is no risk of consuming genetically modified organisms (GMOs). Unlike maize and some wheat varieties, sorghum grains are grown from traditional hybrid seeds combining several sorghum varieties — a natural method used for centuries requiring no biotechnology, making it non-transgenic (non-GMO product).

Sorghum semolina (grits), also called "Moldavian rice," has distinctive taste qualities allowing the production of a wide variety of food products: flour, starch, biscuits, grits, instant products, alcohol, puffed snacks, etc. It is best consumed in its whole form to benefit from its complete nutrient content and can be cooked like rice.

Various sorghum species are rich in antioxidants linked to reduced risks of cancer, diabetes, cardiovascular diseases and some neurological diseases. Antioxidants are found in anti-inflammatory foods and help clean the organism of free radicals which, if uncontrolled, can lead to inflammation, aging and various diseases. The sorghum grain hull has a greater quantity of antioxidants than blueberries, strawberries and plums.

Sorghum flour is increasingly appreciated as a gluten-free alternative to wheat flour. Sorghum flour must be obtained from the whole ground grain. Refined sorghum flour is also available, but like any refined product has a reduced nutrient content.

Due to the fact that sorghum flour has a low glycemic index, and is a product with high starch, fiber and protein content, it takes more time to digest compared to other similar products from refined cereals. This slows the rate at which glucose (sugar) is released into the blood, which is beneficial, especially for people with problems such as diabetics.

Sorghum also keeps you satiated for a long period and prevents blood sugar spikes and drops that can lead to depression, fatigue, unhealthy food cravings and overeating. Some varieties of sorghum bran with high phenol content and high antioxidant status have been found to influence important biological processes relevant to diabetes and insulin resistance.

In African and Asian sub-continents, sorghum is a staple food and most of the grains produced in these countries are used for human consumption in the form of unleavened bread. Kharif sorghum grains can be ground and used for other food products such as snacks and other baked goods (Ratnavathi and Patil, 2013).

Sorghum is consumed in different ways in different parts of the world: tortilla (made from fermented or unleavened dough) called "jovar roti" in India; breakfast porridge or couscous served at dinner in Africa; flour used for thickening stews in some Pacific islands; fermented and non-fermented beverages; or simply consumed as fresh vegetables in some parts of the world.

Ground sorghum (100% sorghum flour that has not been refined) can be used like other types of gluten-free grain cereals for making homemade baked products such as bread, pies, muffins, pancakes and even beer.

From sweet sorghum, delicious syrups, molasses, jam, as well as beverages such as beer, mead, kvass and vodka can be obtained. Interestingly, this is the only plant whose juice contains approximately 20% sugar.

In dietary nutrition, sorghum is used to prepare healthy and nutritious dishes, with grains added to vegetable salads. This product is capable of satisfying hunger for a long period and enriching the body with minerals and vitamins.

In China, the beverage Maotai is made from sorghum grains. In Ethiopia, instead of bread, injera is often consumed — flat cakes made from sorghum dough.

6.2. IN ANIMAL NUTRITION

Through its chemical composition, energy value and high protein content, as well as its low sensitivity to mycotoxins, sorghum offers important advantages in animal feed. The starch content of sorghum (energy source) represents 74% of dry matter; it exceeds that of wheat and equals that of maize. The protein content of sorghum (which averages 11%) can vary between 10 and 12% — in the best cases.

Sorghum can be used as green fodder, concentrate and silage, for both poultry and other large and small animals. With nutritional value close to that of maize, sorghum grains have wide use in fattening cattle and poultry. Sorghum hay is superior in quality to maize, as it contains large amounts of calcium, phosphorus and carotene salts.

In the form of silage, sorghum has the same value as maize silage and ensilages very easily due to its high carbohydrate content. In young stages, sorghum plants contain the cyanogenic glycoside "durrin," which upon hydrolysis and contact with the enzyme "emulsin" in the animal's stomach decomposes and forms hydrocyanic acid. This toxic substance is favored by plant age, drought, low temperatures, weed infestation, excessive nitrogen fertilization and irrigation. The lethal dose of hydrocyanic acid is 1 mg/kg live weight in cattle and 0.1 mg/kg live weight in sheep. Among sorghum varieties, sweet sorghum is not toxic and can be consumed by animals.

Sorghum can be included in feed rations at up to 40%, while also taking into account that this level must be adapted according to the production stage or growth stage of poultry. For example, in the early stages, it is preferable for the incorporation percentage of grain sorghum in rations to be a maximum of 30%.

Improved mutant lines with higher lysine content in the grain also show substantially higher protein digestibility compared to normal varieties (Dowling et al., 2002).

The nutritional qualities of sorghum are also of high interest in pig farming. In growing pigs and those in final fattening stages, the daily gain brought by sorghum is almost identical to that recorded with maize. Sorghum can be introduced in rations alongside maize, wheat and barley. Compared to maize, the nutritional content of sorghum shows a slightly higher amino acid level, while the energy content is slightly lower. Sorghum can be used at all stages of pig production: during reproduction, the growing period and the finishing phase. Due to its essential amino acid content, sorghum shows interesting levels of threonine and tryptophan. In terms of efficiency, average daily gains vary between 98 and 106% compared to maize.

At INCDBNA Balotesti, research was conducted to discover the applicability of sorghum in animal nutrition and find alternative feed materials to the classics, pursuing diversification of raw feed materials through the efficient use of local resources.

Chemical analyses confirmed that white sorghum has a valuable nutritional potential through its protein content (9.91%), with high biological value due to the essential amino acid profile (0.266% lysine, 0.280% methionine + cystine, 0.357% threonine, 0.367% arginine) and energy value comparable to that of maize (3,207 kcal/kg metabolizable energy).

Following experiments on using white sorghum in broiler chicken feed, inclusion at 27–33% — depending on the growth phase, partially substituting (50%) maize — is recommended, with positive effects on production performance, carcass quality indices and the composition of chicken meat.

Sorghum grains contain small amounts of xanthophyll pigments necessary for pigmenting egg yolks or skin in broilers. Using sorghum in laying hen feed requires supplementation with natural pigments (marigold oil, yeasts, etc.) or synthetic pigments to obtain intense yolk coloration. If broiler meat consumers prefer a lighter-colored carcass, the use of sorghum in broiler feed can represent a marketing strategy to reduce carcass pigmentation.

Hens fed sorghum grits grow healthy and lay well throughout the year. Using white sorghum does not have adverse effects on important health indicators such as blood biochemical profile and gastro-intestinal development. At the same time, sorghum improves intestinal microflora by increasing beneficial Lactobacillus spp. populations, possibly due to the bioactive compounds in sorghum that have a beneficial effect on health.

Sorghum represents an alternative for partial replacement of maize in broiler chicken feed, weaned piglets, young cattle and lambs on fattening, as well as dairy cows, especially in the current context of climate change and variation in the availability of the major energy source in the livestock industry.

Other uses of sorghum include: corn-meal substitute and bulk fodder (compound feeds). After harvesting the grain, in grain hybrids, the stalks remain green and succulent, making chopping and ensiling under the best conditions possible. Sorghum for silage is harvested at the milk-wax or wax stage. At this stage, it contains between 20 and 40% sugar in the stalks.

6.3. IN BIOFUEL PRODUCTION

6.3. IN BIOFUEL PRODUCTION

Sweet sorghum stalks contain fermentable sugars capable of producing 400–600 gallons/acre of ethanol — approximately twice that of maize. This makes it one of the leading bioenergy crops globally.

CHAPTER VII

ECOLOGICAL REQUIREMENTS OF THE SPECIES

(Authors: Matei Gh., Isticioaia S.F.)

WATER REQUIREMENTS

The transpiration coefficient of sorghum is lower than that of maize, ranging between 152–190 (Laudi, 1967). Evapotranspiration is on average 3 mm/day in the initial growth stage, with a maximum of 6 mm/day reached at 8–9 weeks after emergence.

Research by Irrig et al. (2000), cited by Antohe (2006), showed different Kc coefficient values (max. evapotranspiration relative to reference evapotranspiration) across the 4 major development stages compared to wheat: at sorghum 0.53, 0.82, 1.24 and 0.85 (initial, vegetative growth, reproductive and maturity stages); at wheat 0.50, 1.36, 1.24 and 0.42 respectively.

Sorghum has high tolerance to extreme relative air humidity values, being able to grow and set fruit at low humidity (below 30%) or high humidity (75–80%). However, the best yields with good crop hygiene, free of pathogen attack, were obtained at 65–70% relative humidity until grain filling, and 55–60% during the wax-to-physiological maturity phase.

Maman et al. (2003) showed that water use efficiency (WUE) — the amount of water used by the plant to produce one unit of yield — has values of 12.4–13.4 kg/ha/mm for sorghum, while for millet these fall in the range 5.1–10.4 kg/ha/mm.

In a study on a range of sweet sorghum hybrids under conditions of sandy soils in SW Oltenia, Draghici et al. (2020) concluded that during the flowering phenophase, leaf transpiration rate in sweet sorghum showed a diurnal variation influenced by the hybrids studied and several environmental factors: light intensity, wavelength of light radiation, leaf water status, relative air humidity and air temperature. Photosynthesis and transpiration processes in the plant correlated significantly and positively (r = 0.92**).

TABLE 7.4 — Water percentage, DM and vacuolar juice concentration in sweet sorghum hybrids at SCDCPN Dabuleni (2018–2020):

- SASM-1: DM 28.6% / total water 71.4% / free water 68.4% / bound water 3.0% / Brix 12.7%
- SASM-2: 26.9 / 73.4 / 70.7 / 2.3 / 12.8%
- ES ATHENA: 28.3 / 71.7 / 68.7 / 2.9 / 13.9%
- BMR GOLD: 25.7 / 74.3 / 70.8 / 3.6 / 14.2%
- SUPERSILE 20: 27.9 / 72.4 / 69.1 / 3.4 / 12.5%
- Average: 27.48 / 72.52 / 69.52 / 2.98 / 13.22%

In general, sorghum's water requirements are low: sorghum consumes on average 20% less water than maize to produce the same amount of dry matter (IRAT, 1991).

Under exceptional climatic conditions with pronounced water stress and relative air humidity below 50%, the phenomenon of panicle resorption before its emergence has been reported. In some genotypes this phenomenon was also favored by a high number of individuals per unit area (high density).

Although it is a plant with adaptations and mechanisms conferring enhanced drought tolerance, sorghum crops placed under irrigated conditions record important yield increases (grain, biomass, juice, panicles).

SOIL REQUIREMENTS

Sorghum is less demanding with respect to soil, valorizing different soil types — from the most fertile to those poor in nutrients and water.

It has generally moderate requirements, predominantly valorizing less fertile, saline and sandy soils on which it ensures, under normal conditions, superior yields compared to other crops placed on these soils.

Regarding soil reaction, sorghum can be cultivated on soils with pH ranging between 5 and 8.5. These lower requirements explain why sorghum cultivation is more extensive in broad areas of the globe with saline or sandy soils (North, East and West Africa, western Asia, southern USA, southwestern Romania).

Lueschen W.E. (University of Minnesota, 1991) recommends that the most suitable soils for sweet sorghum are those with pH greater than 6; sorghum tolerates alkaline soils better than acid ones.

Although for sweet sorghum in the USA various soil fertilities are used, the most suitable for Kentucky and the entire southern US zone have proved to be soils with moderate clay content and sandy loams when cultivating sweet sorghum for syrup production (Morris J. Bitzer, 1991). Avoiding very rich soils with much organic matter is recommended, as these can negatively influence the quantity and especially the quality of syrup obtained.

The soil must have good natural drainage and high water retention capacity; sufficient moisture throughout the entire growing season is a condition on which large stalk and syrup yields depend (Matei, 2006).

Clay soils that are heavy, with slow water infiltration, waterlogged, cold, with water table at the surface, or with oxidation-reduction processes prevailing, are unsuitable for sorghum. However, when water stagnates on soil for a longer period, sorghum demonstrated greater resistance than maize due to the presence of aerenchyma — a physiological adaptation for supplying oxygen for normal development and functioning of the root system.

In Romania, grain sorghum is usually placed on less productive, sandy or saline soils where maize no longer provides economic yields. For sweet sorghum and broom sorghum, productive, fertile soils with good water retention capacity are used.

LIGHT REQUIREMENTS

Sorghum is a short-day plant and behaves as such in response to variations in this vegetation factor. Shortening or lengthening the photoperiod causes plant reactions quantified as delays in flowering or extension of the vegetative period at the expense of the generative period.

Due to its accentuated genetic diversity, sorghum exhibits forms with different responses to photoperiodism: in the tropical zone, forms sensitive to this factor are widespread; in the temperate zone, forms neutral to photoperiod length are encountered. The latter initiate flowering and bloom regardless of whether day length varies between 10 and 12 hours or more; late forms, under a 10-hour illumination period, flower simultaneously with early forms (Antohe et al., 2006).

Research by Ayangar (1939) and Quinby (1958) on the influence of light on pollen viability showed that pollen germinates only under light conditions, even if released during the nocturnal period. Light influences flowering not only through duration but also through spectral composition: red light inhibits floral initiation, while infrared rays have the capacity to accelerate initiation and panicle emergence.

CULTIVATION ZONES IN ROMANIA

Global temperature increase has modified growing conditions in Romania too, with monthly average temperatures and precipitation showing large fluctuations — not so much quantitatively as in terms of the moment of precipitation distribution during the growing season (March–October) of most cultivated species.

Taking these aspects into account, certain zones where maize provided good yields have become more arid and less suitable for maize, leading to the decision to expand sorghum cultivation in these areas, as sorghum resists water shortage better and generates economic grain yields.

Sorghum is recommended to be cultivated with priority in zones with less productive, sandy soils (Dobruja, southern Oltenia), eroded and saline soils (Baragan, Banat, Crisana and Southern Moldova). For sweet sorghum cultivation aimed at obtaining superior biomass and juice yields, rich, structurally sound, deep soils in the Banat, Oltenia Plain, Baragan zone, etc. are preferred.

CHAPTER VIII

CULTIVATION TECHNOLOGY

8.1. CROP ROTATION

(Authors: Matei Gh., Dima M., Popa L.D.)

Sorghum is not demanding with respect to the previous crop, but when establishing its place in the crop rotation, its poor suitability as a predecessor must be taken into account, due to morphological and physiological characteristics.

It requires previous crops that leave the soil clean of weeds, since the weed hazard in sorghum is particularly great because in the first 30 days of the growing season the plant develops its underground part (root system) more, while the aboveground part grows at a slower rate. Species in which annual monocotyledonous weeds are not controlled integrally should be avoided; particular problems in sorghum are caused by Johnsongrass (Sorghum halepense) and bermudagrass (Cynodon dactylon), which can compromise the crop in the early vegetative phases (Matei, 2013).

Sorghum cultivation must be integrated into a rational crop rotation, with maize or soybean as predecessors — crops that leave the soil clean of weeds (Morris J. Bitzer, 1991).

The soybean–sorghum rotation brought important yield increases in grain sorghum (Gakale and Clegg, 1987; Roder et al., 1989a), increased soil nitrogen content (Bagayoko et al., 1992) and improvement of agro-productive soil properties.

For Romania, particularly valuable predecessors are annual legumes (peas, beans, soybeans). Valuable are also cereals/grass mixtures, autumn-sown cereals, fodder beets and annual fodder plants harvested by mid-autumn, but especially perennial plants, after which sweet sorghum will be placed in years 2–4 after their termination (MAA-2000).

Very suitable predecessors for grain sorghum have proven to be small grain cereals (barley, wheat, triticale, rye on sandy soils), early potatoes and cowpeas. In zones favorable to sweet sorghum, the best predecessors are small grain cereals, sunflower, sugar beet and maize.

ROTATION IMPACT STUDY RESULTS:

- In monoculture on sandy soils at SCDCPN Dabuleni: sorghum difficult to maintain, yield only 8.3 q/ha
- In 2-year rotation: 8.8 q/ha (similar to monoculture)
- In 3-year rotation: 12.0 q/ha
- In 4-year rotation: 11.3 q/ha

As a predecessor, sorghum is considered an unsuitable species. Research conducted in 4–5-year rotations showed that following crops record yield reductions of 16–20% in wheat and 42–50% in grain maize after sorghum.

International studies (Kansas, USA, 1996–2015) showed that when sorghum followed wheat in rotation, grain yield was 6,261 kg/ha compared to 3,918 kg/ha when sorghum followed sorghum.

TABLE 8.1 — Impact of grain sorghum–cotton rotation on yield (Texas A&M):

- Sorghum–sorghum: 5,080 lb/acre sorghum
- Sorghum–cotton: 6,224 lb/acre sorghum / 777 lb/acre cotton
- Cotton–cotton: 641 lb/acre cotton

Cotton after sorghum yielded 22% more than cotton monoculture.

Sorghum represents an alternative for renewing the soil. For Romania, after sorghum it is recommended to plant spring crops: sunflower, maize silage, forage mixtures, green mass, etc.

8.2. FERTILIZATION

(Authors: Matei Gh., Isticioaia S.F., Draghici I., Vladut N.V., Ungureanu N., Voicea I., Persu C.)

The specific consumption of sorghum is presented differently in the literature, either per 1,000 kg grain + corresponding stalks, or per total dry matter. On average it is estimated at: 24 kg N, 9 kg P_2O_5 and 8 kg K_2O.

For sweet sorghum, Parisi E. (cited by Bilteanu, 1991) mentions that per tonne of stalks, sweet sorghum consumes 1.7 kg nitrogen and 0.9 kg phosphorus.

RECOMMENDED FERTILIZATION RATES BY SORGHUM TYPE:

- Grain sorghum, non-irrigated: N 50–150 kg/ha; P_2O_5 50–100 kg/ha; K_2O 40 kg/ha
- Grain sorghum, irrigated: N 150–200 kg/ha; P_2O_5 100–150 kg/ha; K_2O 40–60 kg/ha
- Technical/industrial sorghum: N 100–150 kg/ha; P_2O_5 50–100 kg/ha; K_2O 40 kg/ha
- Sweet sorghum: N 50–80 kg/ha; P_2O_5 40–80 kg/ha; K_2O 60–80 kg/ha
- Forage sorghum: N 80–120 kg/ha; P_2O_5 80–100 kg/ha; K_2O 60–80 kg/ha

Nitrogen application to sweet sorghum must be done in moderate doses (50–80 kg/ha active substance). These doses must not exceed the indicated values because nitrogen directly influences the percentage of sugars in the juice accumulated in the stalks (Matei, 2006).

Two critical periods in sorghum nutrition (Muntean et al., 2008):

1. The intensive growth period — manifesting 20–35 days after emergence
2. The period from flowering to the beginning of ripening — when nitrogen deficiency has unfavorable consequences on grain or biomass production

Practical experience has shown the need to ensure nitrogen availability in optimum quantities until the later growth phases.

On sandy soils (psamosols), nitrogen dose should be split into two application stages: at sowing as starter fertilization, and at the 2nd or 3rd inter-row cultivation, depending on soil fertility and moisture regime.

On degraded, humus-poor soils, application of farmyard manure (15–25 t/ha) directly to the crop is recommended.

Fertilization levels applied to sweet sorghum and the types of chemical fertilizers applied should be established only following soil chemical analyses. Among macroelements, nitrogen is used in all situations, and most of the yields obtained depend on the level of nitrogen applied.

Clay soils can ensure large yields in sweet sorghum under moderate fertilization. Sandy soils, however, require larger quantities of fertilizers to ensure a good growth and development rate throughout the entire growing season.

For soils with pH below 6, liming amendments must be used to correct soil acidity. For sorghum, the quantity of amendments used is similar to that used for maize.

Sweet sorghum stalks contain fermentable sugar capable of producing 400–600 gallons/acre of ethanol — approximately 2 times more than maize (per Anderson, University of Iowa, 1988). At a yield of 5–7 tonnes/acre, the sweet sorghum crop extracts from the soil: 100 lb N, 40 lb P_2O_5 and 180 lb K_2O (Smith, 1990).

On sandy soils, nitrogen application is done at 20% at seedbed preparation, with the remainder applied during vegetation when sweet sorghum is 8 to 16 inches tall. Phosphorus and potassium fertilization must be performed based on soil chemical analysis results.

8.3. SOIL TILLAGE

(Authors: Vladut N.V., Matei Gh., Voicea I., Cujbescu D., Ungureanu N.)

[Content covering plowing depth, disk harrowing, seedbed preparation with mechanized equipment developed by INMA Bucharest — pages 160–179 of the monograph]

8.4. SOWING OF SORGHUM

(Authors: Matei Gh., Isticioaia S.F., Draghici R., Cujbescu D., Voicea I., Ungureanu N., Pintilie P.L.)

[Content covering sowing date (when soil temperature reaches 10–12°C at 5 cm depth), seed rates, row spacing, seed treatment, mechanized sowing equipment — pages 180–202 of the monograph]

8.5. CROP CARE OPERATIONS

(Authors: Matei Gh., Trotus E., Isticioaia S.F., Draghici R., Voicea I., Ungureanu N., Cristea O., Diaconu A.)

[Content covering herbicide application, inter-row cultivation, crop protection from weeds, pests and diseases — pages 202–208 of the monograph]

8.6. IRRIGATION OF THE CROP

(Authors: Vladut N.V., Matei Gh., Ungureanu N., Voicea I., Persu C.)

[Content covering irrigation norms, irrigation scheduling, water use efficiency under irrigation conditions, equipment used — pages 208–218 of the monograph]

8.7. HARVESTING OF SORGHUM

(Authors: Vladut N.V., Voicea I., Matei Gh., Isticioaia S.F., Draghici I., Ungureanu N., Cristea O.)

[Content covering harvesting methods for grain sorghum (combine harvesting), sweet sorghum stalk harvesting for juice, harvesting equipment developed by INMA Bucharest, harvesting windows and timing recommendations — pages 218–227 of the monograph]

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CHAPTER IX

DISEASES AND PESTS OF SORGHUM

(Authors: Paraschivu M., Draghici R., Matei Gh.)

9.1. IMPORTANCE OF CROP PROTECTION IN SORGHUM

The success of sorghum crops is frequently conditioned by the occurrence of various diseases and pests which, through their damage, contribute to reducing the production potential of varieties and hybrids below the level of the agrotechnical conditions ensured. In many cases, yield losses can be significant (Barbulescu, 1985, 2002).

Sorghum has a high level of starch, sugar and fiber and is one of the most important energy crops in the world. However, attacks by harmful insects can cause great damage to this plant (Chunshan Guo et al., 2011).

Through research, various control methods have been developed to lead to more efficient management for increasing sorghum production. Grain sorghum is considered a drought-resistant plant with a future perspective in arid zones of Romania (Cojocaru, 1994; Antohe, 2007; Draghici, 2009), given the intensification of atmospheric and pedological drought in the recent period, which obliges finding an alternative to the current assortment of cultivated plants. Anthracnose and rust are important biotic constraints for grain and forage sorghum production globally and are best managed through plant resistance (Rajan Sharma et al., 2012).

Results obtained in the period 2012–2013 for grain sorghum highlighted values of 47.11–41.31% for the attack degree produced by Hadrotrichum sorghi, and 3.73–11.55% for the attack degree produced by Fusarium moniliforme Sheld.

Studies showed the existence of a close link between the degree of pathogen attack and plant resistance to drought conditions, frequently encountered in the sandy soil zone. Thus, at intense plant transpiration — when water loss exceeded 2.8 mmol $H_2O/m^2/s$ — an increase in the degree of attack by Hadrotrichum sorghi and Fusarium moniliforme Sheld was recorded.

Under conditions of temperatures of 31.9–32.5°C recorded at the leaf surface, increased transpiration rates led to increased pathogen attack. Significant and distinctly significant correlations were established between sorghum plant transpiration and the attack degree of these pathogens.

Through damage produced by pathogens to the foliar apparatus of sorghum, the active surface area for photosynthesis is reduced, meaning the plant can no longer produce sufficient nutrients to sustain an optimal growth rate. Leaf hydration is also reduced, as the amount of water in the plant is lost through transpiration.

Expanding sorghum cultivation — due to the numerous advantages this crop offers — will attract new challenges regarding the level pathogen and pest attack can reach, and finding the best integrated control methods and successfully implementing them in sorghum cultivation technology.

Prevention of disease and pest attack is achieved by avoiding placement of sorghum after previous crops that have diseases or pests in common with sorghum, such as: maize (root rot, Periconia circinita, head smut — Sphacelotheca reiliana, fusarioses, corn stripe mosaic, and pests Tanymecus sp., Ostrinia nubilalis — European corn borer, and Rhopalosiphum maydis — black aphids); wheat attacked by Giberella fujikuroi or wireworms; sunflower attacked by Sclerotium bataticola; or heavily infested predecessors of Johnsongrass (Sorghum halepense) which transmits numerous diseases to sorghum (leaf spot — Hadothrichum sp., Helminthosporium sp., Cercospora sp., Gleocercospora sp., loose head smut, etc.).

9.2. DISEASES OF SORGHUM

A. Viral Diseases

SORGHUM MOSAIC (Sorghum red stripe virus — SRSV)

Sorghum red stripe is a virus belonging to the family Potyviridae and is found in all sorghum-growing zones worldwide, capable of reaching an attack frequency of 25–30%, with the capacity to induce stunting, reduction of leaf surface area, chlorophyll content and yield losses of approximately 10% (Toler, 1977, 1979; Pawar et al., 1990).

First symptoms can be observed from June onward. In the early disease stages, small isolated yellow or light-green spots may be observed on leaves. As the disease progresses, spots become rust-brown, and in severe infections leaves turn brown and plants dry out completely.

The virus can also affect Johnsongrass, overwintering in its rhizomes as an obligate parasite, and in spring is transmitted to sorghum via the main vector insects: Rhopalosiphum maidis, Rhopalosiphum padi, Schizaphis graminum and Myzus persicae.

Prevention and control measures:

- Control of Johnsongrass with specific herbicides
- Correct crop rotation
- Control of aphids responsible for virus transmission
- Use of genetically resistant hybrids

MAIZE CHLOROTIC MOTTLE VIRUS (MCMV)

Maize chlorotic mottle virus belongs to the family Tombusviridae and was first reported in Peru, currently being widespread in Argentina, Mexico, Hawaii, Kansas and Nebraska in the USA, and in Europe is present in Spain.

Host plant circle includes maize (Zea mays), barley (Hordeum vulgare), green foxtail (Setaria spp.), Johnsongrass (Sorghum halepense), wheat (Triticum aestivum), and sorghum (Sorghum bicolor).

Symptoms vary depending on genotype, age and environmental conditions, manifesting as mild mottling, chlorotic leaf stripes, through severe plant stunting, necrosis, shortening of panicle inflorescences, short internode formation, and shortening and malformation of inflorescences. In severe infections, necrosis can cause premature plant death, with yield losses varying between 10–15% on production areas and up to 50% in experimental plots.

9.3. PESTS OF SORGHUM

GREENBUG (Schizaphis graminum Rond.)

Since sorghum's introduction to cultivation in Romania (1961–1962), the cereal greenbug (Schizaphis graminum Rond.) has required research attention — a pest that frequently contributes to limiting production and sometimes to crop failure through its damage (Barbulescu, 1985).

Research conducted in 2012–2014 on sorghum grown on sandy soils showed that infestation with the cereal greenbug (Schizaphis graminum Rond.) was recorded 2–3 weeks after emergence, with a frequency of 7.7–40.6% depending on the phytosanitary treatment used.

Results highlighted the very good effectiveness of the product Calypso 480 CE at 80 ml/ha, reducing greenbug attack frequency by 81% compared to the untreated control (which registered a frequency of 40.6%). The same study underlines a negative correlation between attack frequency produced by Schizaphis graminum (Rond.) and chlorophyll content in sorghum leaves, and a positive correlation with the intensification of the transpiration process. Treatment with Calypso 480 CE at 80 ml/ha led to optimization of the transpiration process (Fa% = 7.73; 2.48 mmol H_2O m^{-2} s^{-1}).

Research on chemical control of greenbug (Barbulescu, 1972, 1985) highlighted the most effective insecticides (applied both preventively as granules during sorghum sowing and curatively as sprays, dusts or granules), the number of treatments and the optimal application timing, which depends on the evolution of maximum aphid appearance on sorghum.

An important role in stabilizing sorghum yields is constituted by the control of Schizaphis graminum, whose presence has been favored by the climatic conditions of the zone (Draghici et al., 2015).

CHAPTER X

VALORIZATION OF SWEET SORGHUM

(Authors: Vladut N.V., Matei Gh.)

Sweet sorghum stalks contain up to 20% sugar. In view of this high index, sweet sorghum is used mainly for obtaining syrups and even sugar, through stalk pressing.

Unlike other plants, sorghum behaves well when frozen and then returned to its initial state, without losing texture or taste for products obtained from it.

10.1. PRIMARY PROCESSING AND VALORIZATION AS JUICE

(Authors: Voicea I., Grigore I., Petre A., Ungureanu N.)

One of the methods of valorizing sweet sorghum is processing the juice obtained from pressing the stalks through various technologies to obtain alcohol, which can then be converted to ethanol, bioethanol, etc.

The pulp or waste remaining after juice extraction from sweet sorghum stalks constitutes bagasse. The composition of sweet sorghum bagasse contains: 35–50% cellulose, 20–30% hemicellulose and 15–25% lignin. According to the Sweet Sorghum Ethanol Association, sweet sorghum bagasse contains 32.3% cellulose, 21.2% hemicellulose and 8.3% lignin. The difference in composition is attributed to differences in variety type, soil type and environmental factors (Dar et al., 2018).

JUICE EXTRACTION EQUIPMENT:

Small-scale pressing (artisanal):

For small quantities, presses of small capacity are used — powered by diesel engine or animal (horse), pressing carried out directly in the field, at the farm, or in the home.

Industrial-scale pressing system:

Large sweet sorghum stalk quantities obtained from extensive cultivation cannot be processed by artisanal methods. The industrial pressing station includes: stalk reception system; feeding hopper for the pressing machine; sweet sorghum stalk pressing machine; evacuation conveyor; storage platform for pressed green mass.

INMA Bucharest (National Institute for Agricultural and Food Industry Machines and Installations) developed an experimental pressing installation model (IPTS) with 3 rollers, designed for pressing sorghum stalks to obtain juice for raw alcohol/bioethanol production. Technical characteristics:

- Roller diameter × length: 240/400 mm
- Number of rollers: 3
- Roller speed: 22 rpm
- Drive: 5.5 kW electric motor at 1470 rpm
- Estimated pressing capacity (manual feed): 250–300 kg/hour sorghum stalks
- Pressing efficiency at one pass: 55–60%
- Estimated pressing force: 80–110 kN
- Gap regulation: 12–15 mm at entry of first two pressing drums; 5–7 mm between last two pressing drums

Commercially available 3-roller presses include:

- Kamdhenu Agro Machinery (India): drum diameter 254 mm, 25 HP electric motor, capacity 2.2 t/hour
- Patel Manufacturing Company, Gujarat (India): model OM KAILASH NO.1, capacity 80–100 kg/hour, roller diameter 216 mm, 5 HP motor
- Penagos-Colombia, model SUGAR CANE MILL TH: capacity up to 600 kg/hour, 6 HP electric or 10 HP combustion engine, extraction efficiency approx. 60%
- ITA Mecagro (Republic of Moldova): designed to increase juice extraction by repeated passes through pressing stages

The juice extracted is filtered and then clarified. The viscous part deposited on the storage vessel bottom undergoes rotary vacuum filtration, and the filtrate is concentrated in the evaporation section. Concentration to 16–18 Brix is recommended for ethanol production. For seasonal storage, concentration must be raised to a minimum of 65 Brix.

10.2. PRODUCTION OF SYRUP FROM JUICE OBTAINED BY PRESSING SWEET SORGHUM STALKS

(Authors: Voicea I., Ungureanu N., Grigore I., Petre A.)

Sweet sorghum is one of the sorghum varieties with stalks of high sugar content and is cultivated mainly for juice, forage, silage and syrup production. Syrup is an antioxidant-rich food material produced by concentrating the sweet juice or sugar.

Due to the juicy sweet stalk, sweet sorghum is an excellent source of ethanol and syrup production. In the food vs. fuel debate, food must always take priority. In addition, syrup obtained from sweet sorghum has good antioxidant properties and is useful in food, beverage and pharmaceutical industries. Syrup is also a good substitute for honey in nutraceutical formulations. Declining natural honey production has led to growing demand for sweet sorghum syrup in the last decade.

Syrup is obtained from sweet sorghum juice by boiling to approximately 75 Brix, resulting in a consistency and appearance similar to honey. Due to the syrup's chemical composition, its shelf life is also high.

The National Institute of Agroforestry Research (NARI, India) has been concentrating efforts on sweet sorghum syrup production since the 1990s, today being the only organization in India that produces and sells sweet sorghum syrup. Initially using a single hybrid (Madhura-1) developed within the organization, recently two new varieties — Madhura-2 and Madhura-3 — have been successfully used for syrup production (Rajvanshi et al., 2020).

A major impediment in the industrial production of sweet sorghum syrup was historically the difficulty of storage and preservation under optimal conditions, due to sugar crystallization in winter and juice fermentation in summer. Current studies have demonstrated that when syrup is properly made, it can be kept for an extended time in well-sealed containers, provided they are not agitated.

10.3. PRODUCTION OF FOOD CARBOHYDRATE CONCENTRATES FROM SWEET SORGHUM JUICE

(Author: Nenciu F.)

[Content covering concentration technologies, refractometric analysis, quality parameters for food-grade concentrates — pages 285–288 of the monograph]

10.4. PRODUCTION OF FEED CARBOHYDRATE CONCENTRATES FROM RAW SWEET SORGHUM JUICE

(Author: Nenciu F.)

[Content covering technology for producing animal feed carbohydrate concentrates — pages 288–299 of the monograph]

10.5. VALORIZATION OF SORGHUM AS BIOETHANOL AND FOOD-GRADE ETHYL ALCOHOL

(Authors: Nenciu F., Constantin O.)

[Content covering fermentation technology, distillation, bioethanol yields (4,152–9,157 L/ha from sweet sorghum stalks), comparison with other biofuel crops — pages 299–322 of the monograph]

10.6. VALORIZATION OF BY-PRODUCTS AND WASTE FROM ALCOHOL PRODUCTION

(Authors: Nenciu F., Constantin O.)

[Content covering distillery by-products (spent mash/vinasse), recycling and valorization options — pages 322–324 of the monograph]

10.7. VALORIZATION OF SWEET SORGHUM STALKS AS HEMICELLULOSIC CARBOHYDRATES AND BIOETHANOL

(Authors: Buruiana C.T., Istrati D.I., Vizireanu C., Furdui B.)

[Content covering lignocellulosic biomass processing, xylose and pentose extraction from bagasse, second-generation bioethanol production — pages 324–330 of the monograph]

10.8. VALORIZATION OF SWEET SORGHUM AS BIOGAS

(Authors: Ungureanu N., Voicea I., Gageanu I.)

[Content covering anaerobic digestion of sweet sorghum biomass for biogas production, methane yields, biogas installation design — pages 330–345 of the monograph]

10.9. VALORIZATION OF TECHNOLOGICAL WASTE FROM SORGHUM AS COMPOST

(Authors: Nenciu F., Ungureanu N., Gageanu I., Nae G.)

[Content covering composting of sorghum processing waste, compost quality parameters — pages 345–374 of the monograph (continued in Vol 4)]

10.10. VALORIZATION OF SWEET SORGHUM THROUGH PYROLYSIS AND GASIFICATION

[Continues in Volume 4]

10.11. NUTRITIONAL VALUE OF SORGHUM BICOLOR GRAIN AND VALORIZATION AS FOOD PRODUCTS

[Continues in Volume 4]

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CHAPTER X (CONTINUED)

VALORIZATION OF SWEET SORGHUM

10.10. VALORIZATION OF SWEET SORGHUM THROUGH PYROLYSIS AND GASIFICATION

(Author: Ungureanu N.)

PYROLYSIS OF SWEET SORGHUM BAGASSE

Pyrolysis of sweet sorghum bagasse yields three products: bio-oil (liquid), biochar (solid) and syngas (gaseous). According to Piskorz et al. (1998), both whole sweet sorghum and sweet sorghum bagasse are suitable raw materials for producing organic liquids through fast pyrolysis. However, bagasse yields better results and a higher-quality liquid (for fuel). During pyrolysis of sweet sorghum bagasse:

- Biochar production decreases with increasing reactor temperature, due to degradation of hemicellulose, cellulose and lignin
- Pyrolysis oil yield increases with temperature due to cellulose degradation
- Yield decreases due to formation of non-condensable gases/volatile substances comprising primarily CO, H_2, CO_2, CH_4 and N_2 (Naik et al., 2017)

GASIFICATION OF SORGHUM BIOMASS

Among dominant thermochemical technologies, gasification is considered the most cost-effective and efficient for converting lignocellulosic biomass into bioenergy (De Lasa et al., 2011). Gasification technology has been known for over 100 years.

Gasification is a thermochemical transformation process of solid or liquid biomass at high temperatures and often high pressures, into a mixture of carbon monoxide, hydrogen, carbon dioxide, methane, tar, water vapor, hydrogen sulfide and traces of other species. The fractions are determined by operational variables such as raw material characteristics, gasification media (steam, air, O_2, CO_2), temperature and pressure inside the gasifier, and catalysts (Sikarwar et al., 2017).

Through gasification, intermediate products (bio-oil) and final products (synthesis gas or syngas) are obtained, with potential for conversion to biofuels (Atsonios et al., 2015).

Syngas obtained from biomass contains many contaminants — tars, particles, alkalis, nitrogen, sulfur, halides and trace elements — and for this reason can be subjected to purification processes before burning or use in catalytic reactors for heat or power generation. Syngas can also be used for methanol and ammonia production.

Using air as gasification medium dilutes syngas with nitrogen, increasing downstream processing costs and yielding low calorific value (4–6 MJ/m^3). Using oxygen avoids this but is costly; oxygen-enriched air can be used as a compromise. Steam as a gasification medium produces H_2-rich syngas usable as feedstock for producing more biofuels through catalytic chemical synthesis.

Burning gaseous fuels has inherently higher efficiency than solid materials, because oxidation of solids in oxygen/air occurs gradually from the exterior surface inward (heterogeneous process), while syngas can be burned at a very high mass transfer rate (homogeneous process).

TABLE 10.5 — Comparison between biomass gasification and direct combustion (Mai and Nguyen, 2020):

- Feedstocks: Gasification can use wet, low-energy-density biomass; direct combustion requires optimal moisture and relatively inflammable biomass
- Flame: Gasification (if syngas purified) produces no soot, dust or toxic gases; direct combustion produces soot, dust, toxic gases
- Heat exchanger surface impact: Gasification prolongs heat exchanger life; direct combustion reduces it due to silica smoke, dusty aerosols and corrosive gases
- Internal combustion engine applicability: Gasification — yes; direct combustion — no
- Equipment design: Gasification — complex; direct combustion — simple
- By-products: Gasification — charcoal, ash (solid), tars, bio-oil, wood vinegar (liquid); direct combustion — ash only

GASIFICATION SYSTEM TYPES:

TABLE 10.6 — Main characteristics of gasifier categories (Zhang et al., 2019):

- Fixed bed: Small capacity (0.01–10 MW); suitable for large, coarse biomass particles; low syngas temperature (450°–650°C); high particle content in syngas; can produce high tar content (0.01–150 g/Nm³)
- Fluidized bed: Medium capacity (1–100 MW); advanced technology; uniform temperature distribution; better gas-solid contact; high operating temperature (1000°–1200°C); low particle content in gas stream
- Entrained flow: Large capacity (60–1000 MW); suitable for fine-grained biomass (0.1–0.4 mm); very high operating temperatures (1200°C); not suitable for high-ash biomass; very high oxygen requirement; negligible tar production

SWEET SORGHUM IN GASIFICATION PLANTS:

Sweet sorghum can be used as feedstock in fixed-bed gasification plants for generating industrial heat. Sweet sorghum biomass is an ideal substrate for producing combustible gases such as hydrogen through gasification (Hu et al., 2017).

Recommended moisture content for gasification: 15%; particle size below 4 cm. Sweet sorghum is fed continuously into the gasifier. The combustible gas produced (CO, H_2, CH_4, tar and dust) has a calorific energy of 1,000–1,200 kcal/Nm³.

For improving sweet sorghum bagasse quality before gasification: torrefaction (mild pyrolysis at 200–300°C in inert atmosphere) destroys the fibrous structure, removes moisture and oxygen through dehydration and carboxylation reactions, doubling energy density, calorific value and carbon percentage. At 250°C with 30-minute retention time, initial moisture of energy sorghum can be reduced from 7.83% to 2.05%, and sweet sorghum moisture from 9.29% to 5.51% (Yue et al., 2017).

Calorific value of syngas: 4–7 MJ/m³ using air as gasification agent; up to 10–18 MJ/m³ using pure oxygen or steam as agents (Wei et al., 2020).

BIOMASS COGENERATION PLANTS using gasification technology can operate with varied power groups from 50 kW to 1 MW. Biomass consumption (woody or agricultural): 0.850 kg/kWe; operating period: 8,000 h/year; installed electrical power: 50 kW–10 MW.

Advantages of cogeneration biomass plant:

- Total gas emissions much lower than large-capacity plants
- No gas emissions to atmosphere during fuel conversion, significantly reducing air pollution

- Diesel engines of generating sets adapted to run on syngas with emissions several times lower than conventional diesel engines
- Greatly reduces or completely eliminates environmental pollution with various waste types
- Maximizes energy potential of biomass waste

INTEGRATED MULTIFUEL GASIFICATION (IMG) TECHNOLOGY — a four-stage autothermal gasification process (biomass feed, drying, gasification, slag vitrification) followed by plasma conditioning of produced gas. The syngas obtained is a clean combustible gas with low calorific value, usable directly in gas engines for thermal and electrical energy generation; slag is inert.

IMG Technology specifications:

- Maximum waste processing capacity: 12 t/h
- Syngas volume: 14,700 Nm^3/h
- Syngas calorific value: 4.2 MJ/Nm^3
- Energy consumption: 1.4 MW
- Plasma generator energy consumption: 400 kW
- Net gas combustion efficiency in engine: 40%
- Electrical efficiency in cogeneration: 55%
- Thermal efficiency in cogeneration: 80%
- Gasification efficiency: 80–85%

Advantages of IMG technology: all tars decomposed; all toxic radicals destroyed; no NOx emissions due to reducing atmosphere in absence of oxygen; no dioxins generated.

10.11. NUTRITIONAL VALUE OF SORGHUM BICOLOR GRAIN AND VALORIZATION AS FOOD PRODUCTS

(Authors: Istrati D.I., Buruiana C.T., Vizireanu C., Furdui B., Apostol L.)

Preoccupation with functional ingredients and food health properties has been accentuated in recent decades. Functional foods are those that, beyond the basic nutritional effects common to all food products, contain biologically active components with health benefits. Apart from macronutrients and micronutrients — for example, vitamins and minerals that are efficient in small amounts — a functional food also contains, in certain concentration groups, secondary plant metabolites, components of constitution that have additional effects on human health beyond the effects attributable to essential nutrients, with beneficial effects on one or more physiological functions that go beyond adequate nutrition (Roberfroid, 2000; Ozena and Kilic, 2011). These are involved in the processes of oxidative stress regulation, cardiovascular health, glycemic control, immune function improvement, cancer prevention and bone health.

SORGHUM AS A FUNCTIONAL FOOD:

Sorghum grain represents an important source of starch, proteins, lipids, vitamins, dietary fiber and bioactive substances. As a gluten-free cereal, sorghum has significant importance as a functional food for celiac disease sufferers and those with gluten sensitivity.

The high content of phenolic compounds in sorghum — particularly 3-deoxyanthocyanins (3-DXA) that are unique to sorghum — gives it exceptional antioxidant properties. Condensed tannins in sorghum are well-known antioxidants.

FOOD PRODUCTS FROM SORGHUM GRAIN:

Traditional products worldwide:

- Injera (Ethiopia) — flat bread made from fermented sorghum dough

- Ugali/Uji (East Africa) — porridge/gruel
- Ogi/Akamu (West Africa) — fermented porridge
- Bhakri/Jowar roti (India) — flatbread
- Tô (West Africa) — stiff porridge
- Boza (Southeast Europe/Central Asia) — fermented grain beverage
- Opaque beers: dolo (Burkina Faso), pombe, umqombothi (South Africa)
- Kaffir beer (South Africa)
- Maotai spirit (China)
- Baijiu (China) — various distilled spirits

Modern food applications:

- Gluten-free bakery products (bread, biscuits, muffins, cakes)
- Sorghum pasta and noodles
- Ready-to-eat breakfast cereals
- Sorghum popcorn (puffed sorghum)
- Sorghum flour for composite flours
- Baby food formulations
- Sorghum beer (craft brewing)
- Functional food ingredients (dietary fiber, phenolic extracts)

RESEARCH RESULTS FROM PROJECT 9/PCCDI/2018:

Research conducted on Sorghum bicolor flour (from 8 hybrids grown at SCDA Caracal and SCDA Secuieni) demonstrated:

1. Sorghum flour as a functional ingredient:

- High dietary fiber content (2.35–3.07% crude fiber as prebiotic)
- Rich in iron (qualifying for EU "source of iron" claim under Regulation 1924/2006)
- Significant magnesium and zinc content (>50% of FDA daily value)
- Gluten-free — suitable for celiac disease patients

2. Bread-making quality of sorghum flour:

- Composite flour formulations with wheat flour achieve acceptable bread quality at 20–30% sorghum substitution
- Pure sorghum bread (gluten-free) achieves improved texture with addition of hydrocolloids (xanthan gum, guar gum)
- Sorghum flour bread has lower glycemic index than wheat bread

3. Bioactive compounds:

- Total phenolic content: 0.8–4.2 mg GAE/g DM depending on hybrid and processing
- Antioxidant capacity (DPPH): significantly higher in colored-grain sorghum
- 3-deoxyanthocyanins unique to sorghum show superior chemical stability compared to common anthocyanins

4. Sorghum grain for food fortification:

- Protein content 9.46–12.21% (comparable to wheat)
- Essential amino acid profile with leucine, valine, histidine and isoleucine exceeding FAO/WHO/UNU recommended daily intake
- High in B vitamins (thiamine, riboflavin, niacin, pyridoxine)
- Mineral-rich: iron, phosphorus, potassium, magnesium, zinc

SYRUP AND SWEETENER PRODUCTS:

Sweet sorghum syrup composition (per tablespoon, 20g):

- Calories: 62

- Carbohydrates: 15g
- Key nutrients: iron, calcium, potassium
- Contains no protein or fat (pure syrup)
- Antioxidant activity: 4× that of natural honey (Kulkarni et al., 2018)
- Sugar composition: 50% sucrose + 25% fructose + 25% glucose (vs. pure sucrose in commercial sugar)
- Rich in essential and non-essential amino acids, polyphenols, macro and microelements, vitamins

Applications:

- Natural sweetener in food and beverages
- Substitute for honey in nutraceutical formulations
- Ingredient in confectionery, ice cream, sauces, dressings
- Fermentation substrate for vinegar production
- Traditional condiment (used in place of molasses in Southern USA cooking)

[END OF VOLUME 4 TRANSLATION]

[Bibliography and index sections follow in the original Romanian text]