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REVIEW ARTICLE

Sorghum (*Sorghum bicolor* L. Moench) and Its Main Parts (By-Products) as Promising Sustainable Sources of Value-Added Ingredients

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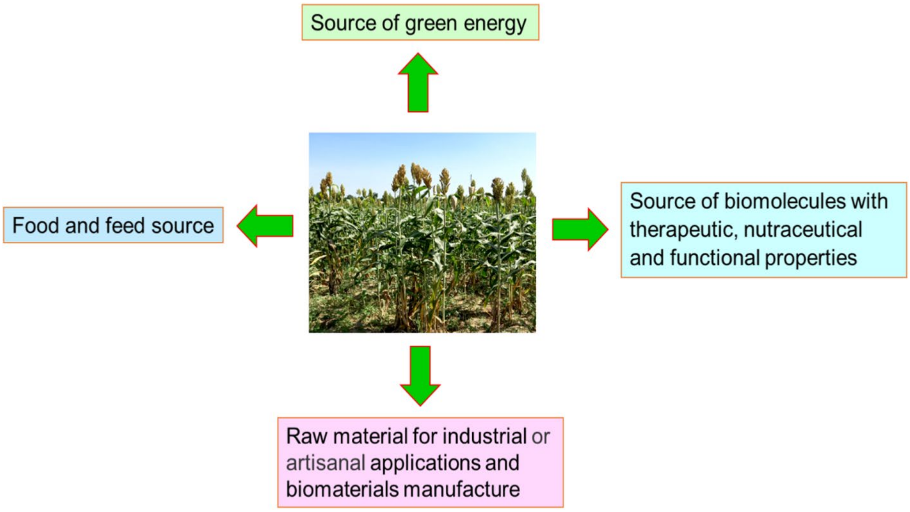
Abstract

Sorghum (*Sorghum bicolor* L. Moench) is a flowering plant in the grass family (Poaceae) characterized by a great genotypic and phenotypic diversity, making it a cereal species of major interest cultivated in warm climate worldwide. Fifth most cultivated cereal in the world and second in Africa, sorghum is the main cultivated species in the Sahelian zone. In 2020, its world and African estimated production were 58.7 and 27.5 million tonnes over an area of 40.3 and 27.3 million hectares, respectively. Primarily cultivated for its seeds, fodder, sugar and fiber, or for bioenergy production, sorghum is a staple food for millions of people. Its polymorphism gives it a versatile, multifunctional character and allows it to combine different food, energy and industrial uses. Mainly studied as a feedstock for the production of several chemicals and biofuels including bioethanol, biomethane, biohydrogen, biolipids, butyric and lactic acids, 1-butanol, acetone-butanol etc. and for electrical energy production in microbial fuel cells. The processes for exploiting the various components (starchy grains, lignocellulosic biomass and sweet juice extracted from the stem) of this plant generate a large quantity of by-products which are valued in many fields of application. Mainly as source of food and feed, biomolecules with therapeutic, nutraceutical and functional properties and for industrial or artisanal applications and biomaterials. The world population increasing combined with the decrease of biomass resources, due to the effects of climate change, imposed a reconsideration of the potential of the entire value chain of this crop. The present review focused on the biochemical composition of sorghum and its use as food but also as a source of valuable by-products.

Graphical Abstract



Keywords Sorghum · By-products · Food · Energy recovery

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Statement of Novelty

This review demonstrates the resilient potential of sorghum for multiple uses in a current context marked by the natural resources depletion, concern about global warming and food and energy security. The relevance of exploring and exploiting the sorghum genetic diversity is related to the fact that it combines both the starch storage in the seeds and a large quantity of carbohydrate's accumulation in their juicy stems as well its resistance to extreme agronomic conditions. The production and exploitation value chain of sorghum around the world generates enormous quantities of by-products with various compositions. The recovery of this biomass makes the sector economically and ecologically more profitable and much more attractive compared to other crops. It is assumed that, sorghum currently ranks fifth among cereals after wheat, maize, rice and barley, but its versatility and multifunctional character places it as a crop that will prosper in the near future for sustainable development.

Introduction

Sorghum (*Sorghum bicolor* L. Moench) is an important cereal grass used as a staple food for humans and animals in Africa, Asia, Australia and Central America [1]. Sorghum is an important resource of minerals, vitamins, proteins, antioxidants and starch [2]. In terms of production and plantation area, sorghum grain is considered the fifth most important cereal after wheat, maize, rice and barley [3]. Grown on an average area of 43.2 million hectares worldwide (period 1998–2020), the global production of sorghum varies between 58 and 64 million tonnes per year [4, 5]. In sub-Saharan Africa, it ranks second after maize, with an estimated production of 27.5 million tonnes in 2020, over an area of 27.3 million hectares, i.e. 67.8% of the world's average planted area [5]. This popularity of sorghum is due to its resistance to drought, its low input requirement, its hardiness [6–8], its high yield in biomass [9, 10] and various applications in the economy. Its culture and production system are also well understood. Sorghum also has a very high genetic diversity characterized by adaptability to a wide range of environmental conditions with the ability to grow in temperate and tropical climates and to resist saline and alkaline soils, thus offering the possibility to be grown in marginal or semi-arid areas. Global population growth combined with the policy of some developing countries to develop the industrial exploitation of sorghum grains (brewing) have led to an increase in demand for sorghum throughout the world and particularly in Africa. Moreover, the reduction of natural resources imposes the absolute necessity of valuing agricultural by-products in order to improve the global economy. To this end, sorghum combining both starchy grains and high sugar contents stems has interesting potential making it a top candidate feedstock source. Indeed, sorghum has a very high green biomass yield estimated between 20 and 120 tonnes/ha, depending on the growing conditions and the botanical characteristics of the plant material [11]. The primary valorization of this biomass presents a significant by-product potential, still recoverable in various forms of value-added products. Compared to plants that produce lignocellulosic biomass, sorghum, which photosynthesizes in C4, is notoriously interesting for the size and speed of its vegetative growth [12]. This unique resilient and versatile plant offers a wide range of food and feed applications [13–15], industrial or artisanal [16, 17] and energy [18, 19] applications as well as for biomaterials manufacture. Traditionally, sorghum has a multitude variety of uses. In human food all parts of sorghum (grains, sweet and juicy stems) are used in the composition of various forms of food including couscous, porridge, donuts, pasta, cakes, breads, alcoholic drinks, food syrups or crystallisable sugar etc. [20, 21]. Regular consumption of sorghum grains has many health benefits due to its strong antioxidant activity, cholesterol-lowering, anti-inflammatory and anticancer properties, its potential to reduce the risk of cardiovascular disease, certain types of cancer and type II diabetes [22]. Its low gluten content makes it a particularly interesting food for people who are allergic to it [23, 24]. Sorghum stems, leaves and rachis are also used as a material for dwellings and broom making. In animal feed sorghum is a source of starch, carbohydrates, polyunsaturated fats (PUFAs), amino acids, minerals, vitamins and certain essential amino acids [25–27]. Sorghum and its co-products have been also considered as a source of nutraceuticals and functional, due to the phenolic properties of their compounds [28], which also act as antioxidants and chemopreventive agents [29]. Sorghum stems are lignocellulosic biomass mainly composed of cellulose, hemicelluloses and lignin [30, 31]. It can be used as feedstock for high added-value products manufacturing such as bioplastics and bio-composites [32, 33], biodegradable films [34, 35] or for manufacturing of furfuraldehyde, used in lubricants, adhesives, and nylon [8, 36]. The main free and water-soluble sugars contained sorghum stems are sucrose, glucose and fructose, in varying proportions depending on the sorghum varieties [37, 38]. These soluble sugars are often recovered for the production of energy vector biomolecules such as bioethanol, biomethane, biohydrogen, biolipids, and for electrical energy production in microbial fuel cells. The food exploitation (of the seeds) of this cereal grass generates important by-products which are valued in various forms and presenting innovative and best perspectives for future sustainable development that the present work strives to identify.

Sorghum Resource

Morphology

Sorghum is an annual plant that is characterized by a cylindrical, straight, sturdy, full stem that ends in a large, branched or compact inflorescence called a panicle. The general morphology of a mature cultivated sorghum plant is shown in Fig. 1. The plant has a main stem. This can have a number of secondary stems starting from its base, called basal tillers. Each stem is made up of a stack of identical morphological units called a phytomer [39]. The phytomer consists of a leaf, a node with an axillary bud and an internode developed below the node. For a given stem, the phytomers are emitted successively by the apical meristem, a zone of cell division and differentiation located at the tip of the stem. Sorghum typically consists of around 75% stem, 10% leaves, 5% seeds and 10% roots by weight [40]. This composition varies according to varieties, cultivars and growing conditions. The raw composition of sorghum has been reported as 37.28% juice, 36.01% bagasse, 19.14% leaves and 7.58% tassel on a wet basis [41]. The height of the stem in cultivated sorghum varieties ranges from 50 cm at maturity for the shortest up to 5 to 7 m with 4 cm in diameter for the tallest [39, 42]. The size of the leaves increases with their row on the stem to a maximum and then decreases steadily for the 4 to 6 terminal leaves. Leaf's size also varies depending on the variety and growing conditions. Thus, the length of the leaves varies from 30 to 135 cm and the width from 1.5 to 13 cm [39]. The roots are adventitious fasciculate and originate on the very short internodes at the base of the stems. They are 25 to 30 cm long and form a very important hair. Some of them are able to quickly descend to a depth of 2 cm to extract water and minerals. This characteristic gives to sorghum its quality of hardiness and drought resistance. This architectural description was also made in 2012 by Whitfield and some authors [43] who grouped sorghum into three important varieties. The first variety is grain sorghum which is three to six feet in height (0.9 to 1.8 m) and which produces large ears used primarily for food. The second variety is sweet sorghum having a height which generally ranges from eight to twenty feet (2.4 to 6 m). This variety has thicker and fleshier stems than those of grain sorghum but with smaller ears. The third variety is forage type and is similar to the sweet variety, but the plants are generally smaller and have lower levels of water and sugars [43].

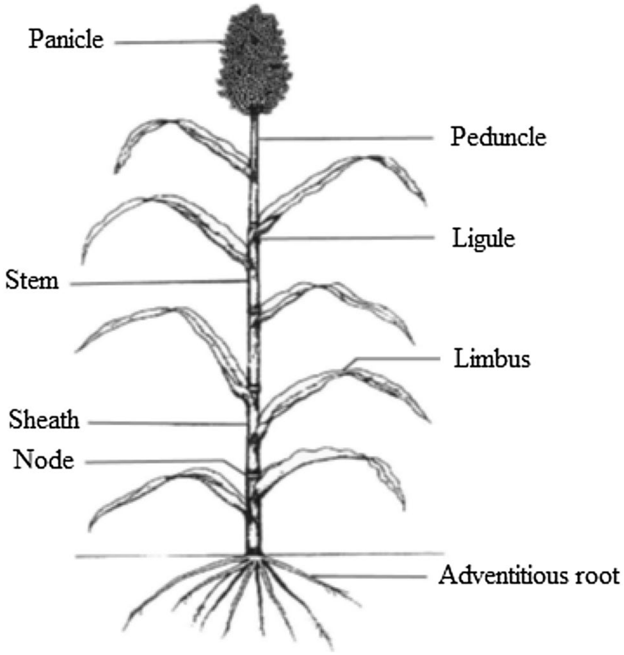

Fig. 1 Diagram of a sorghum plant with a single main stem [44]

Origin and Distribution

Common sorghum (*Sorghum bicolor*) is a cereal and fodder grass of African origin [42, 45, 46]. More precisely, it would come from the border region between the Ethiopia and Sudan [47, 48]. It is one of the oldest cultivated species in the world even if the time of its domestication remains unclear. It would have been domesticated about 6000 years before Jesus Christ, in North-East Africa, between Sudan and Ethiopia, on the Southern edge of the Sahara, where the oldest archaeological remains have been found [49]. It is currently cultivated almost everywhere in the world thanks to genetic advances. Sorghum is assumed to have reached Asia around the third millennium BC with inter-continental migrations. It reached Europe in Roman times (753 BC), then America in the sixteenth century [50]. In addition, sorghum has agronomic characteristics suitable for hot and dry climates as well as tropical and temperate climates. Sorghum is cultivated in all continents as shown in Fig. 2.

Taxonomy

From its scientific name *Sorghum bicolor* L. Moench, sorghum is a cereal grass belonging to the family of *Poaceae* (formerly Grasses), subfamily of *Panicoïdeae*, tribe of *Andropogoneae* and of *Sorghum* genus [48]. Sorghum is a monoecious species which is preferentially self-pollinating. The Sorghum genus comprises 20 to 30 species [52] and most cultivated sorghum varieties belong to the *sorghum bicolor* species. This species exhibits very high genotypic and phenotypic variability [42, 53]. In addition to the variations in size at maturity, the Sorghum genus is characterized by an extraordinary polymorphism. The color of the

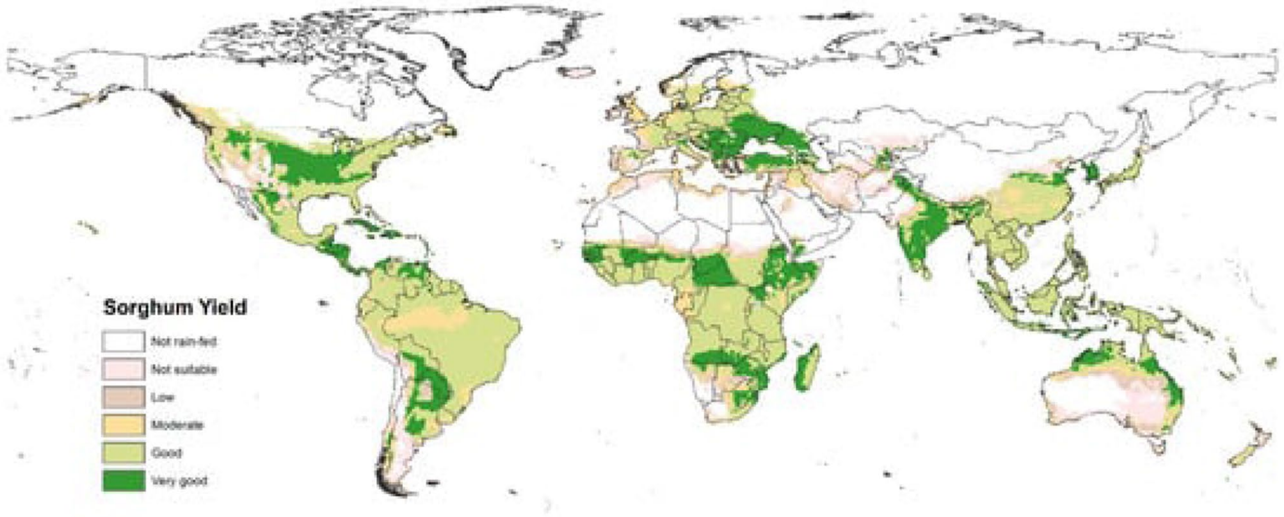

Fig. 2 Spatial distribution of the sorghum cultivation area [51]

sorghum grain varies from white, pale yellow or pale orange, beige, red, to deep red-brown, passing through different shades of red and brown [54–57]. Figure 3 illustrates this phenotypic and genotypic diversity of sorghum grains.

Cultivated sorghum presents a great diversity of forms described by different botanical classifications. The first classification taking into account all wild and cultivated sorghums of the *Sorghum* genus was established by Snowden [58]. It defines two sub-genera or sections including a total of 52 species: 28 cultivated and 24 wild. According to the classification of Doggett [48], the *Sorghum* genus is divided into five sections. Among them is the Sorghum section, composed of two wild and perennial species, *S. propinquum* and *S. halepense* as well as an annual species, *S. bicolor*. The species *S. bicolor* is itself divided into three subspecies. The subspecies *S. bicolor spp. bicolor*, which includes cultivated sorghum in which five main races are distinguished, the subspecies *S. bicolor spp. drummondii* (weed sorghum) and the subspecies *S. bicolor spp. Verticilliflorum* (wild sorghum). The most recent and widely used classification is that of Harlan and de Wet [47]. It is based on characteristics of the spikelets (glume and grain) and the shape of the panicles. Five basic breeds are distinguished, namely the *bicolor, guinea, caudatum, durra* and *kafir* races, as well as the 10 two-by-two combinations of these basic races (such as *durra-caudatum*, *kafir-caudatum* or *guinea-kafir* sorghums…). Table 1 presents the main identity characteristics of the basic sorghum breeds. *Bicolor* sorghum

Fig. 3 Illustration of the genotypic and phenotypic diversity of mature sorghum panicles (**A**) black (left), white (middle), and red (right) [57], Adapted from [25]; and different pigmentations of sorghum grains (**B**) [56]

Table 1 Main identity characteristics of sorghum breeds

Race	Glumes [39]	Grains [39]	Panicles [39]	Area of dominance [47, 65]
Bicolor	Long glumes covering ¾ or all of the grain	Weight of 1000 grains from 15 to 25 g	Loose panicles	African savannah, South East Asia
Guinea	Glumes usually long, open	Elliptical grains, more or less flattened dorso-ventrally, of variable size	Loose panicles semi-loose, often long with drooping port	West Africa Savannah, India, South East Asia
Caudatum	Short glumes adhering to the grain by covering it partially	Unsymmetrical grains, medium to large	Compact panicles semi-compact, trendy shape fusoid	Tropical Africa
Durra	Short glumes adhering to the grain by covering it partially	Grains more or less spherical, sized variable but most often fat to very big	Compact panicles to semi-compacts often worn by a crossed peduncle	Near East and India
Kafir	Short glumes adhering to the grain by covering it partially	Elliptical grains, medium sized, 1000 grain weight from 20 to 35 g	Panicles moderately compact, often long and cylindrical	Africa, South of Equator

varieties often have a sweet stalk. In addition, these present specific types such as broom, paper or fodder sorghums [39]. For this, another fully functional classification exists, it classifies the varieties according to their main use (grain, fodder, sweet or biomass sorghum). Sweet-stemmed sorghum varieties, mainly of the *bicolor* race [47, 59–61], group together different ecotypes whose common characteristic is accumulation of significant amounts of carbohydrates in their juicy stems [62, 63]. These varieties, called sweet sorghums, were historically determined respectively as *Holcus saccharatus* (L.), *Andropogon saccharatus* (R.) and *Sorghum saccharatum* (Pers.) at the end of the nineteenth century, before finally being classified within *S. bicolor* [64]. There are approximately 4000 cultivars of sweet sorghum distributed throughout the world.

Production and Cultivation Requirements

Sorghum has an African origin but its great genetic and phenotypic diversity makes it a species of major interest cultivated around the world [64]. Indeed, common sorghum (*Sorghum bicolor*) ranks fifth in the world among cereals after wheat, rice, maize and barley with a production varying between 58 and 64 million tonnes per year [4, 5] on an average area of 43.2 million hectares (period 1998–2020), that is 6.4% of total cereal area and 2.7% of cereal production. In sub-Saharan Africa, it ranks second after maize, with an estimated production of 27.5 million tonnes in 2020, on an area of 27.3 million hectares, that is 67.8% of global average areas devoted to this cereal [5] and it is the most cultivated species in the Sahelian zone. In Africa, the areas of significant cultivation are in the belt stretching from the Atlantic to Ethiopia and Somalia [50]. The production yields in 2020 were estimated at 1458.5 kg/ha and 1006.4 kg/ha respectively in the world and in Africa [5]. These figures cover significant disparities between the different producing countries. For example, in 2020, the yields were: 4594.6 kg/ha for the United States, 989.1 kg/ha for Bourkina Fasso, 3150.1 kg/ha for Brazil, 1690.2 kg/ha for Cameroon and 4579.2 kg/ha for France. These differences are mainly linked to agro-ecological constraints, levels of intensification, and the botanical characteristics of the plant material in the different growing areas. Sorghum has a very high yield of green biomass estimated between 20 and 120 tonnes/ha depending on the growing conditions and the botanical characteristics of the plant material [11]. For the sweet sorghum variety, for example, yields vary from 32 to 112 tonnes/ha (fresh biomass) and from 15 to 25 tonnes/ha (dry biomass), depending on the cultivar, climate, locality and cultivation practices [66]. In Africa sorghum is grown in a diverse range of environments from the north to the south of the continent. Sorghum, however, is grown mainly in West Africa, Northern Central Africa and East Africa. Table 2 presents the productions and production yields of sorghum in certain regions of the world.

Sorghums are drought and heat resistant [67–70]. They require few inputs and have relatively short cultivation cycles (3–4 months) compared to sugar cane (> 9 months). They present a very important genetic diversity offering possibilities of adaptation to temperate and tropical climates. Sorghum requires less fertilizers, the necessary inputs of nitrogen (N) for example are much lower than those of most intensive crops such as maize for an equivalent yield [71, 72]. Given its short cycle (4 months), it is quite possible in areas where rainfall and meteorological conditions allow it, to carry out two harvests per year [73]. Sorghum requires much less water, its consumption is around 8000 m^3/ha harvested, that is about a quarter of the water used by sugar cane and almost half of the water used by maize for an equivalent yield [42, 71, 74, 75]. The optimum ranges of rainfall for growing sorghum vary from 400 to 800 mm and those for relative humidity from 15 to 50% [39, 76]. Sorghum can be

Table 2 Sorghum production, cultivated areas and production yields in the world. *Source* [5, 51]

Region	Years														
	1990			2000			2010			2015			2020		
	P	A	Y	P	A	Y	P	A	Y	P	A	Y	P	A	Y
World	56.8	41.6	1.4	55.8	41.1	1.3	60.2	42.2	1.4	66.0	41.6	1.6	58.7	40.3	1.5
Africa	11.9	16.4	0.7	18.4	21.1	0.9	25.0	26.1	0.9	26.2	25.8	1.0	27.5	27.3	1.0
Americas	22.6	7.3	3.4	23.2	7.0	3.3	22.5	5.9	3.8	27.4	7.0	3.9	20.3	5.5	3.7
Asia	18.6	17.2	1.0	11.3	11.9	0.9	10.4	9.4	1.0	9.2	7.7	1.2	9.2	6.9	1.3
Europe	0.6	0.3	2.5	0.8	0.2	3.3	0.7	0.1	4.5	1.1	0.3	3.2	1.3	0.3	4.0
Australia & New Zealand	0.9	0.4	2.5	2.1	0.6	3.4	1.5	0.5	3.0	2.2	0.7	3.0	0.4	0.2	1.9

With, *P* production in millions of tonnes, *A* area in million hectares, *Y* yield in tonnes/ha

grown in a temperature ranging from11 to 42 °C with an optimum temperature for growth and photosynthesis of 32 to 34 °C. Sorghum does not have any particular requirement in terms of soils. However, the best yields are obtained on deep or sandy clay soils, a little humus, with a slightly acidic pH and containing nitrogen and potash [46, 77].

Operating Processes and Associated By-Products

Sorghum has a wide variety of uses, whether in human food (flour, semolina, drinks, etc.), in animal feed (grain sorghum, fodder sorghum, silage), in agro-energy (sweet sorghum, biomass sorghum) or even in agromaterials (sorghum fiber) [39, 77, 78].

Harvesting sorghum is one of the operating processes that generates significant by-products, the importance of which varies depending on the sorghum breed, variety and growing conditions. Leaves, stems, shelled panicles and regrowth are the main post-harvest residues of sorghum cultivation. In Africa, they are little or even not valued, most often left on the plot, and are generally used as fruitless pasture in situ, for cattle, goats and horses. This, therefore results in a loss of resources by trampling, because the uncrushed dry stems have a low palatability and are little valued [79]. They are often burnt during the soil preparation for the next sowing and contribute to its organic fertilization. The stems and leaves are also used as a material for dwellings; the very long and loose rachis of broom sorghum is used for broom making. For example, sorghum crop residues generate 2–3 million tonnes of lignocellulosic biomass waste every year in Nigeria. Less than 40% of this biomass is used as feed for livestock and as a thatch cover, while more than 60% is abandoned and burnt in the fields, which accentuates environmental degradation and health risks [80, 81].

The high phenotypic and genotypic variability in sorghum allows its use in various fields. Thus, varieties with sweet stems are used as a candy where they are chewed after removing the lignified epidermis [48, 82]. The stalks of these same varieties are also used to extract sorghum juice, which can be used for the production of bio-fuels, food syrups or crystallisable sugar, depending on the juice sugar content [20]. The fiber residues obtained after pressing constitute the bagasse which can potentially be upgraded in several ways, in particular for the production of energy vectors such as bioethanol [83], hydrogen and methane [84], steam or electricity [85]. It can also be used as fodder, green fertilizer or to manufacture biodegradable food packaging [64]. The process of producing crystallized sugar from the filtered and concentrated juice also generates a by-product called molasses, whose fermentation by yeasts, then distillation and dehydration lead to the production of ethanol.

Sorghum is the staple cereal for many populations in the dry tropics of Africa, Asia and Central America where most of the production is self-consumed [20]. Its low gluten content makes it a particularly interesting food for people who are allergic to it [23, 24]. In Sudano-Sahelian Africa, sorghum seeds are used in preparations in whole form or, more often, after dehulling and milling operations. The flour obtained is used in the composition of various forms of food, including thick pasta, thick porridge such as *tô* from West Africa (Burkina Faso and Mali), fermented cakes such as *kisra* from Sudan and the Chad *kissar*, unleavened breads, couscous, donuts, etc. [20, 21]. Sorghum is sometimes used in the manufacture of infant flours, foods given to children from the age of four to six months in addition to breast milk. These flours are made from roasted grains such as corn (46%), sorghum (21%), soy (18%) to which 8% sugar and 7% powdered milk are added [39]. The sorghum grain transformation processes (shelling, milling, sifting, etc.) for human consumption also generate valuable by-products, mainly bran and residues from shelling and sifting operations.

Sorghum flour can also be used in the composition of beverages, mainly craft beers in Africa and a kind of wine (*baijiu*) in China. Making beers from sorghum is a common tradition in most producing regions. In Africa, we find *dolo* from Burkina Faso, *tchapalo* from Benin, *bilbil* from Cameroon, *ikigage* from Rwanda, *impeke* from Burundi, *pito* from Nigeria or *kaffir* beer from South Africa [39]. After distillation, the residue from processing sorghum into beer is in the form of dry seeds, called spent grains. These can be used as feed for livestock.

In urban areas, industries use sorghum grain base products (flour and semolina) in simple form or mixed with other cereals, for the manufacture of various products: breads, cookies, pasta, beers, etc.

Biochemical Composition of By-Products and Their Food, Technological and Functional Interests: Valuation in Human Food

Biochemical Composition of the Stems

Sorghum stems are lignocellulosic biomass made up of a central part of medullary parenchyma often called the pith, and a peripheral lignin-rich area called the bark. The dry matter content of the stem represents on average 30% of its fresh mass [69, 86]. The moisture content is higher in the pith (77%) than in the bark (56%) on a wet basis [87, 88]. It is mainly composed of cellulose (30 to 45% dry mass), hemicelluloses (16 to 30% dry mass) and lignin (15 to 20% dry mass) [30, 31]. Cellulose and hemicelluloses are complex structural sugars made up of β-(1,4)-D-glucans chains and are much more concentrated in the marrow. Hemicellulose consists of polysaccharides chains known as xylans which are made up of xylose units linked together by a β-(1,4) bond. It can be used as raw material for high added-value products manufacturing such as biodegradable films [34, 35]. When hydrolyzed, xylans result in xylose oligomers called xylooligosaccharides [89] which can be valued in human and animal food, for ethanol production or for manufacturing of furfuraldehyde, used in lubricants, adhesives, and nylon [8, 36]. Lignin, a phenolic polymer, concentrates in the bark and forms a matrix around celluloses and hemicelluloses and increases the resistance of the stem (Fig. 4). It is an amorphous polymer formed mainly of phenylpropane units linked by C–O–C and C–C bonds. Unlike cellulose, lignin does not consist of a single repeating monomer, but has several substituted phenolic units.

Soluble sugars, mainly hexoses (glucose, fructose) and sucrose are stored in the marrow and represent another important part of the content of an internode (5 to 50% of its dry biomass depending on the genotype and the environment). These free and soluble sugars, contained in the stem in the form of juice, often in large quantities for sweet sorghum varieties, are easily extractable. The main sugars contained in this juice are sucrose, glucose and fructose, in varying proportions depending on the agronomic conditions and sorghum varieties [37, 38]. The chemical composition

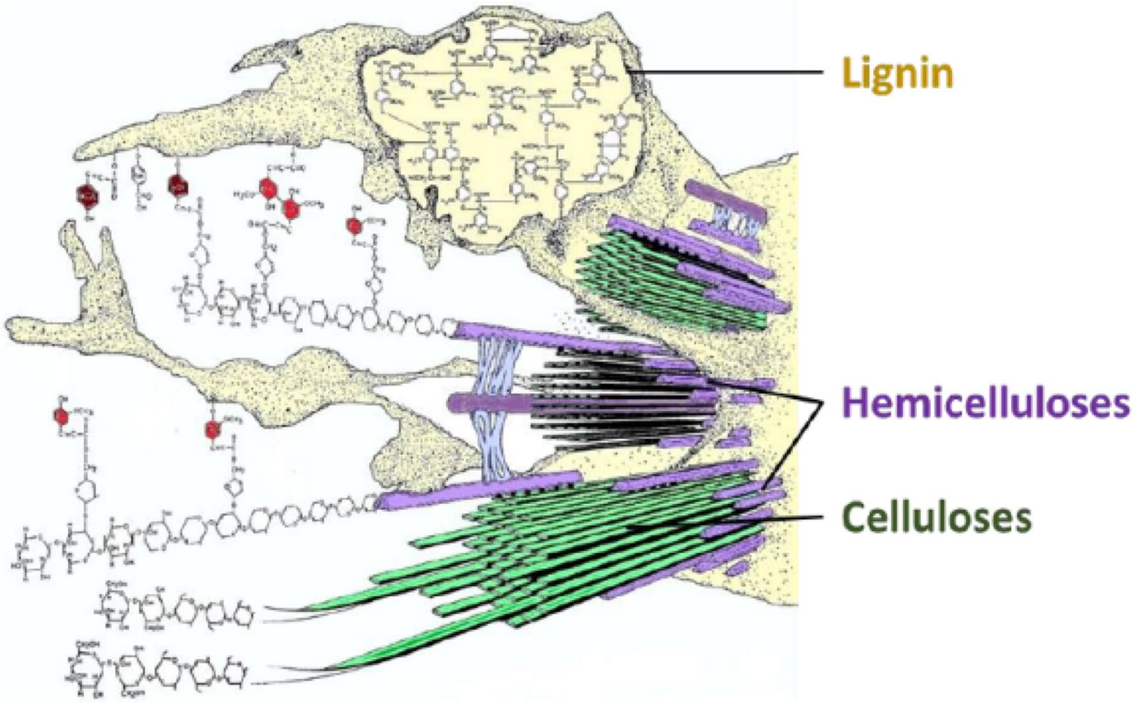

Fig. 4 Illustration of the molecular structure of the structural sugar fibers encompassed by the lignin polymer [90]

of sweet sorghum (leafless) stalk, bark and pith is shown in Table 3.

Techniques and Technologies for Extracting Juice from the Stems

Mechanical pressing and diffusion are the techniques used to extract free sugars from the stem of sweet sorghum. However, before the extraction operation, a biomass pretreatment is necessary in order to improve the sap extraction efficiency. The way the stems are chopped, cut, with or without the leaves, the separation of the pith and bark, as well as the time between harvesting and pressing have an impact on the juice extraction yield [95, 96]. Pressing only the pith contained in the stem of sweet sorghum is more efficient in terms of sap extraction than pressing the entire stem [97]. However, the separation of the stem from the leaves brings one more step that can compromise energy yield in addition to taking more time [98]. The standard process for extracting sugar from sorghum can be likened to that of cane and beet sugar. In the literature, it is possible to distinguish four main types of presses used for pressing sweet sorghum, namely screw presses, roller presses, belt presses and hydraulic presses [94]. Hydraulic roller press technology or cylindrical mills, used in the sugar industries, is often used to extract sugar from sorghum. The percentage of sap extracted depends on the speed of the press, the moisture content of the biomass as well as the various adjustments of the press. But this process is slow, laborious, and less efficient, with sap extraction yields ranging from 30 to 60% of the initial mass [18, 43, 99, 100]. This low juice extraction yield could be attributed to the relatively high fiber content of the stems of sweet sorghum compared to sugar cane [101]. Another disadvantage associated with the grinding process is the loss of sugar due to microbial activities [43, 74]. For this reason, several research works have been carried out to further improve this technology and make it more economical. The development of a series of roller mills in tandem with a counter-current flow of the juice to leach the soluble materials has made it possible to achieve a sugar extraction yield of around 87% [101]. The development of an extraction method (Fig. 5) with double chopping which made it possible to obtain a juice containing more than 80% of sugars initially present in the sorghum stems with a bagasse containing 40% moisture [102]. A comparative study between screw and hydraulic press was also carried out by Crépeau et al. [103]. To this end, the screw press was more efficient than the hydraulic one from the point of view of the juice extraction rate but nevertheless required a stage of filtration of the juice, since it contains more residues than that obtained with the hydraulic press. Other experiments have also been carried out to improve the extraction of sugars from the sweet sorghum stems by adding water to bagasse. For this purpose, several parameters were taken into consideration, namely the size of the rods, the solid/liquid ratio (g of rods/mL of water added) and the incubation temperature with stirring after adding

Table 3 Chemical composition of sweet sorghum stalk (without leaves), pith and bark

References	Structural composition of biomass in (%) DM				
	Stem stripped			Marrow	Bark
	[78]	[91]	[92]	[87]	[87]
Cellulose	12.4	20.1–26.1	21.9–35.6	8.7	19.2
Hemicellulose	10.2	11.7–17.2	21.2–41.2	6.3	17.5
Lignin	4.8	5.1–11.3	18.2–21.5	0.6	8.8
Sucrose	55	9.6–17.6	–	67.4	32.2
Glucose	3.2	0.6–1.6	–	3.7	2.4
Fructose	–	0.3–1.0	–	–	–
Ash	0.3	–	–	0.2	0.5

	Biomass sugar content (g/kg DM)			
	[88]	[93, 94]	[46]	[88]
Total sugars	497.8	56.4–104.7	249.3–256.1	376.3
Soluble sugars	176.5	–	–	228.7
Reducing sugars	41.9	–	–	55.4
Fructose	–	20.4–32.1	70.7–76.4	–
Glucose	–	25.2–39.1	65.4–71.8	–
Sucrose	–	2.4–34.9	107.9–107.9	–

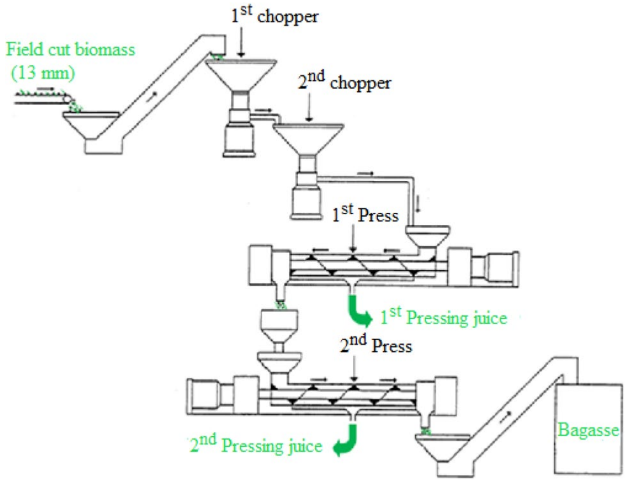

Fig. 5 Process of extracting juice from sweet sorghum [102]

water [104]. The results showed that very fine grinding, an incubation temperature of 30 °C and a solid/liquid ratio of 0.6 g/mL are the most favourable conditions for extracting the maximum amount of sugars. Under these conditions, the first pressing cycle extracts up to 90% of the sugars while after the second pressing, 99% of the sugars are extracted [104]. A similar study was also carried out by Djomdi et al. [88]. They indicated that a solid/liquid ratio of 1/1, a temperature of 45 °C and a duration of 30 min of bagasse impregnation, were the most optimal conditions for maximum and efficient extraction for both soluble and reducing sugars. These conditions made it possible to obtain extraction rates evaluated on average at 59.54 and 82.42%, respectively for the soluble sugars and the residual reducing sugars contained in the bagasse from the first pressing.

Diffusion is also one of the techniques used to extract juice from sorghum stems. It is an operation of transferring soluble compounds from the raw material to a solvent, mainly water. It is defined as "the net transfer of matter from a region of high concentration to one of low concentration" which is due to thermal molecular movement until a state of equilibrium is reached [105]. In order to facilitate the extraction of the juice, the biomass is cut and crushed into fine particles of uniform sizes, then crossed by hot water (70–80 °C) counter-current circulating, where the soluble matter of the juice of the rod passes in solution through the wall of the particles according to the laws of diffusion [106]. Sugar are driven (transfer) by the concentration gradient from the high concentration region to the low concentration one according to Fick's diffusion law [105, 107, 108].

Diffusion, which is a natural phenomenon tending to re-establish equilibrium as soon as there is a concentration gradient, obeys to Fick's law [Eqs. (1) and (2)] according to which the quantity of substance which diffuses per unit time is proportional to the concentration gradient, direction and diffusion direction [109].

$$\frac{d_q}{dt} = -D.S.\frac{dC}{dx} \tag{1}$$

where $\frac{d_q}{dt}$ is the mass of the matter which diffuses per unit of time; $\boldsymbol{D}$ the diffusion coefficient; **S** the surface through which the diffusion takes place and $\boldsymbol{dC}$, the concentration gradient.

If $\boldsymbol{C_1}$ is the concentration inside the cell, $\boldsymbol{C_2}$ the concentration of the water surrounding the biomass particle, and $\boldsymbol{K_e}$ the extraction coefficient (which includes diffusion, surface area and particle thickness), the extraction rate is expressed (variation of concentration as a function of time) by:

$$\frac{dC_1}{dt} = -K_e \cdot (C_1 - C_2) \tag{2}$$

The extraction progress $\boldsymbol{\eta_L}$ is obtained by integrating Eq. (2). It is given by:

$$\eta_L = \frac{C_1 - C_{2,0}}{C_i - C_{2,0}} = \exp\left(-K_e \cdot t\right) \tag{3}$$

With, $\boldsymbol{C_i}$ the initial sugar concentration of the biomass and $\boldsymbol{C_{2,0}}$ that of the extraction water.

There are four types of diffusers: the horizontal rotating tube diffuser, the carpet diffuser, the screw diffuser and the tower diffuser. In general, the diffusion method is the more efficient because it provides a very high extraction yield, estimated at around 98.8% [106]. The diffusion system is also more energy efficient and requires less maintenance and low capital costs due to the lack of excessive pressure and the shear forces of the roller mills [110]. Diffusion plants typically include dewatering mills that use about half the power required in an energy-intensive hammer mill [111].

Dietary Benefits of Biochemical Elements: Valuation in Human Food

The food valuation of sorghum stalks mainly concerns sweet sorghum varieties. This variety, grouping together different ecotypes, is characterized by the accumulation of large amounts of non-structural free sugars in their juicy stems [62, 63]. These free sugars are extracted in the form of juice and consumed in various forms (used to produce sugar, syrup or fermented into food ethanol). The main sugars contained in this juice are sucrose, glucose and fructose, in varying proportions depending on the sorghum varieties [37, 38]. The average composition of the fermentable juice of sweet sorghum is 53 – 58% sucrose, 9 – 33% glucose and 6 – 21% fructose [112]. According to Saballos [11], the juice extracted from the stems is composed of 89% sucrose, 8% simple sugar (glucose and fructose) and 3% starch. Table 4

Table 4 Sweet sorghum stem juice sugar content

Concentration of sugars in g/L					
	[93]	[113]	[94]	[46]	[88]
Sucrose	1.36–66.55	2.2	66.6–79.8	30.54	71.40
Glucose	24.66–32.73	61.2	20.0–21.0	21.54	–
Fructose	19.91–26.80	36.9	16.1–17.9	15.99	–
Total soluble sugars	60.89–111.10	100.3	103.2–118.7	67.34	98.85

shows the concentrations of the different sugars in the juice extracted from the sweet sorghum varieties.

The juice rich in sugars obtained after pressing the stems successively undergoes filtration and concentration operations by boiling and gives a thick and viscous syrup that is consumed today to replace corn syrup, honey or maple syrup (Fig. 6) [11, 114]. This filtered juice, after concentration is also used for granulated sugar production. This operation also generates another by-product called molasses, whose fermentation by yeasts, then distillation and dehydration lead to the production of food ethanol [39]. The juice can also be fermented directly into food ethanol.

Chemical Composition of By-Products and Their Food Interests: Valuation in Animal Feed

Chemical Composition and Nutritional Value of Sorghum Grain Exploitation Residues

Sorghum grain residues from husking, milling and sieving operations (bran and semolina) have a chemical composition similar to that of grains. Several authors have studied the sorghum grain composition and its co-products and have indicated that it is a good source of energy, carbohydrates, polyunsaturated fats (PUFAs), amino acids, minerals, vitamins and certain essential amino acids [25–27]. The contents vary from 6.2 to 14.9% in proteins, 54.6% to 85.2% in carbohydrates, 1.3% to 10.5% in lipids, 0.9% to 4.2% in ash and 1.4% to 26.1% fiber. These variations would be related to grain genotypes, agronomic conditions, as well as certain characteristics specific to cultivars [57, 115]. As in all cereals, starch is the main storage form of carbohydrates in sorghum grain. Starch contents vary between 55.6 and 75.2%, with an average value of 69.5% [25, 39, 116]. The starch of albumen consists of 70–80% amylopectin and 30–20% amylose. The presence of non-starch polysaccharides (NSPs) in sorghum grains could suggest their potential ability to improve bowel function and lower cholesterol levels [117, 118]. Table 5 shows the chemical composition of sorghum grain. Sorghum also contains some of the essential and non-essential amino acids, mainly alanine (7.34–9.62 g/100 g), aspartic acid (4.83–7.06 g/100 g), glutamic acid (17.5–28.12 g/100 g), leucine (12.02–14.48 g/100 g), phenylalanine

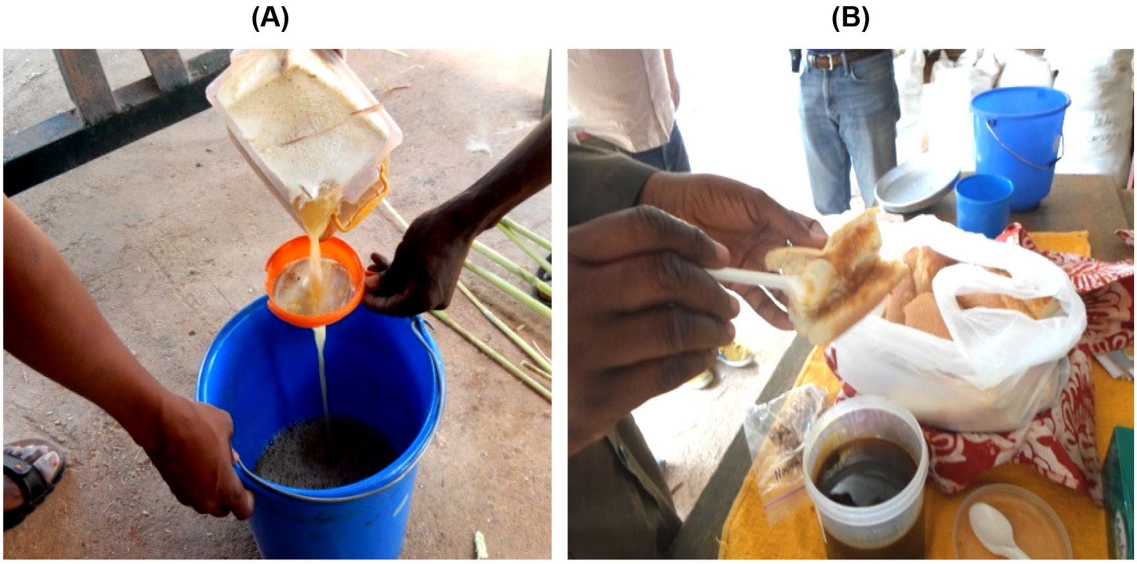

Fig. 6 Sweet Stem Sorghum Juice *extraction and filtration* (**A**) and sorghum Syrup (**B**) [114]

Table 5 Chemical composition of sorghum grain

	Proximate composition (% DM)								
	[53]	[127]	[128]	[129]	[130]	[131]	[132]	[133]	[134]
Protein	4.4–21.1	9.10	9.35	8.90–11.02	10.21–13.45	6.23–13.81	10.48	8.9	4.27–6.06
Fat	2.1–7.6	3.10	3.35	2.30–2.80	2.84–3.02	5.12–10.54	2.97	3.7	6.72–9.26
Ashes	1.3–3.3	2.07	1.98	0.92–1.75	1.28–1.78	1.12–1.68	6.94	1.7	1.67–2.32
Crude fibers	1.0–3.4	2.86	2.25	1.40–2.70	1.72–2.02	1.65–7.94	2.01	1.2	1.45–2.41
Starch	55.6–75.2	76.51	72.41	70.65–76.20	72.44–77.28	65.16–76.28	61.24	73.50	70.55–73.53
amylose	21.2–30.2	–		–	–	–	–	–	–
Soluble sugars	0.7–4.2	–		–	–	–	–	–	–
Reducing sugars	0.05–0.53	–		–	–	–	–	–	–
Moisture	–	6.36	10.66	8.10–9.99	6.67–7.29	1.39–19.02	6.69	–	10.23 – 11.9
Energy (kcal/kg)	–	–	–	–	–	–	–	4120	4020 – 4275

(4.03–5.62 g/100 g), proline (6.66–12.34 g/100 g) and valine (4.22–6.86 g/100 g), but limited in lysine and tryptophan. It does, however, have benefits of bioactive peptides and protein fractions as well as cationic peroxidase, which exerts anti-cancer, antiviral, antioxidant, cholesterol-lowering and antihypertensive effects [119–122]. Sorghum contains fairly high levels of potassium (K) (900–6957.67 mg/kg), and phosphorus (P) (1498–3787.25 mg/kg), minerals known to aid muscle movement, keeping healthy nervous system and building strong bones and teeth. Sorghum is also a source of minerals such as Ca, Fe, Mg, Zn [123] and of B complex vitamins, fat soluble vitamins [124]. Sorghum and its co-products have been considered a source of nutraceuticals and functional due to the phenolic properties of their compounds [28], these compounds constitute one of the most important groups of natural antioxidants and chemopreventive agents [29]. Besides its strong antioxidant activity, sorghum grain also has good cholesterol-lowering, anti-inflammatory and anticancer properties. Regular consumption of sorghum grain is linked to the potential for reduced risk of cardiovascular disease, certain types of cancer and type II diabetes [22].

As with all cereals, the digestibility of sorghum grain varies enormously depending on the genetic makeup. Sorghum grain starch has the lowest digestibility among cereals, due to resistance to digestive enzymes in the hard peripheral layer of the endosperm [125]. However, low tannin varieties and cultivars appear to have the same digestibility as corn [126].

Nutritional Value of Sorghum Fodder and Silage

The nutritional value of forages and silages depends on the content and form of nutrients such as nitrogenous matter, neutral detergent insoluble fiber (NDF), acid detergent insoluble fiber (ADF), non-structural carbohydrate (NSC), fats and minerals [135]. The chemical composition and nutritional value of sorghum forages and silages can vary depending on the sorghum variety, the agronomic conditions and the stage of development at harvest. Sorghum forages and silages are characterized by high sugar content, which could improve nitrogen use efficiency and increase production in cows [136]. The total nitrogen contents of forage sorghum vary from 6.2 to 13 g kg^{-1} DM, relatively lower values compared to those of corn and alfalfa forages [137–139]. However, it has high NDF fiber contents which vary between 505 and 704 g kg^{-1} DM, as well as ADF fibers which vary from 297 to 458 g kg^{-1} DM [140]. Another essential indicator for assessing nutritional value is the estimation of the digestibility of nutrients in forages, such as in vitro digestibility of dry matter (IVDDM) and NDF fiber (IVDNDF). Digestibility is often considered to be the best parameter for estimating the nutritional value of forage, since it is closely related to the proportion of energy available to the animal and therefore to animal performance [136]. The in vitro digestibility of the dry matter (IVDDM) of forage sorghum varies from 542 to 730 g kg^{-1} DM and it is similar to that of sweet sorghum evaluated at 589 g kg^{-1} DM [138, 140, 141]. The fiber contents of forage sorghum silage, estimated on average at 373 g kg^{-1} DM and 626 g kg^{-1} DM respectively for ADF and NDF are similar to those of sweet sorghum silage [140]. However, sweet sorghum silage exhibits lower lignin content, higher in vivo digestibility of NDF, and higher IVDDM than grain sorghum and brown vein sorghum silages [142]. The digestibility of the cellulose of fodder sorghum goes from 72% during bolting to 48% during flowering, then rises a little and stabilizes. The energy value of sorghum fodder varies from 4200 to 4300 kcal/kg DM and its protein intake varies between 58 and 67 g/kg DM [20]. Sorghum fodder is also a source of minerals such as Ca, P, in sufficient quantity to meet the ruminant needs and variable according to the sorghum varieties.

Food Interests of By-Products: Valuation in Animal Feed

This valuation covers all varieties of sorghum and concerns both by-products from the first processing of seeds and stems. In animal feed, because of their nutritional value and digestibility, fodder and silage are the staple food for their growth, metabolism and milk or meat production [135]. In addition to fodder varieties, grain sorghum crop residues such as stems, leaves, regrowths and shelled panicles, are crushed and often mixed with grain brans to serve as fodder, used in ruminant feed, especially cattle, sheep or goats [20, 79]. Bagasse, a residue resulting from the processes of extracting sugars from sorghum stems is also used as fodder (simple or mixed with bran) for feeding ruminants, having a higher biological value for animals than bagasse from sugar cane [74, 143]. For every 10 tonnes of crushed sweet sorghum, 5 to 6 tonnes of wet bagasse can be obtained [144]. The solid residue obtained from the fermenters after the production of ethanol is also a by-product, which can be used in animal feed.

The by-products of the first grain processing of sorghum (brans, semolina, grains) have better nutritional value, and are also used in animal feed, especially for monogastrics such as pigs and poultry feed [20, 39, 79]. Indeed, the bran of sorghum, the grain hulling operation by-product, mainly consists of the husks (pericarp and testa) rich in fiber, protein and minerals and germs (embryo and cotyledon or scutellum), rich in proteins, lipids, minerals and vitamins and representing 10 to 12% of the grain [39]. The major mineral elements in sorghum are P and K and are mostly concentrated in the peripheral layers of the grain and in the germ. According to Boudries Nadia [53], sorghum bran is low in protein and ash and high in fiber and the germ is high in ash, protein, oil and B-complex vitamins, but very low in starch. It also indicates that more than 68% of the total mineral matter and 75% of the oil of the whole grain is in the germ, of which the contribution to the protein content of the grain is only 15%.

Energy Recovery Techniques

Biochemical Process Energy Recovery of Sorghum Stems

Sorghum, a C4 plant, is a unique and versatile sugar crop that can be separated into starchy grains, soluble sugar in the juice extracted from the stem and lignocellulosic biomass [12, 145]. All these components can be converted into ethanol with three main strategies [84, 101, 146].

Sweet sorghum stems are one of the most attractive biomasses used as a raw material for the production of 2G bioethanol, an alternative source to 1G bioethanol produced from starch. The non-structural sugars contained in sorghum juice can be directly converted into bioethanol by anaerobic fermentation under the action of certain micro-organisms, such as *Saccharomyces cerevisiae* and *Zymomonas mobilis* [74, 147–149]. The production yield of bioethanol from sweet sorghum juice varies from 85 to 93% [112, 148, 150]. To this end, several studies have been carried out with a view to improving the yield of ethanol production. For example, the co-fermentation of juice and starch from sorghum grains, improves ethanol yields by almost 30% while reducing the enzymatic hydrolysis time of starch by 30 min compared to the conventional method [150]. In addition, the bagasse obtained after juice extraction is also the raw material for the production of lignocellulosic bioethanol [39, 151, 152]. However, the conversion of lignocellulosic biomass to bioethanol requires a preliminary delignification pretreatment to expose the cellulose and hemicellulose to hydrolysis. The main methods used can be classified into physical, chemical, physicochemical, thermal and biological pretreatments [153]. In general, the yield of bioethanol production from the stems of sweet sorghum, estimated on average at 6106 L/ha, is much higher than that of sugar cane (4680 L/ha) [154]. Several authors have also reported that the yield of bioethanol production from the stems of sweet sorghum evaluated between 1250 to 5625 L/ha, is equivalent to that obtained from 9000 to 11,250 kg of sorghum grain [155, 156]. The energy yield of upgrading sorghum stalks to ethanol is between 6500 to 8900 kJ/kg and 1400 to 2700 kJ/kg of dry and fresh sorghum biomass respectively (assuming the energy yield of ethanol is 26,500 kJ/kg) [157–159]. The major advantage of the valorization of sorghum stalks for the 2G bioethanol production, is that it does not or little compete for the food use of the grains, and moreover, it contributes to a greater reduction in greenhouse gas emissions (− 50% compared to conventional fuel and − 10% compared to 1G biofuel) [160, 161]. However, the short harvest period of the stems, combined with the extreme instability of the juice after extraction, constitute the greatest challenges to his use [150].

Biological Process Energy Recovery of Sorghum Stems

The energy recovery of lignocellulosic biomass by biological process has economic and environmental advantages over other technologies. Biomass can be converted into fuel gases, such as methane and hydrogen, which has recently been characterized as the fuel of the future [162]. However, a pretreatment step is also necessary to delignify the biomass before the production of CH_4 by anaerobic digestion or of H_2 during dark fermentation [163]. Chemical, physicochemical and biochemical conversions are the most promising technologies for depolymerizing lignocellulosic biomass into fermentable sugars [164].

The anaerobic digestion process is based on the natural anaerobic degradation of biomass by micro-organisms, leading to the production of biogas with biomass gas yields of around 14,000 to 16,000 m^3/ha for ensiled sorghum [39]. The methanogenic potential of sorghum stem varies according to its biochemical composition and its structure, and therefore its variety, its period or time of harvest, its growing conditions, etc. In a study involving 4 genotypes cultivated on 3 sites, it was shown that the impact of the genotype was 36% and that of the growing environment 34% on the methanogenic potential of sorghum [9]. With a C/N ratio estimated at 27.625 [165], the methanogenic potential of sorghum stem is estimated between 270 and 335 $NmL_{CH4}.gvs^{-1}$ [166]. And that of sweet sorghum bagasse is 78 LCH_4/kg biomass [84]. Several studies have been carried out with a view to improve the yield of biogas production from sorghum stalks, in particular through pH stabilization techniques, adjustment of the C/N ratio, supply of mineral elements (Fe, Ni, Zn, Ca, etc.) by co-digestion. Zhang et al. [167] showed that the adjustment of the C/N ratio to 25 of the sorghum substrate, and its co-digestion with cow manure allows to obtain a production of around 478 L/kgvs, and an increase in biogas yield of around 26% compared to monodigestion of sorghum stalks. On the other hand, Kalamaras and Kotsopoulos [168] showed that the co-digestion of sorghum with bovine manure was similar to that of maize (267 and 241 LCH_4/kgvs, respectively).

Carbohydrates are the main sources of hydrogen during fermentation processes and therefore carbohydrate-rich agricultural residues such as sorghum stems can also be considered as potential sources of hydrogen [169, 170]. Microbial species of the genus *Clostridium sp*. which produce hydrogen by fermentation have a great affinity for the simple sugars (glucose, fructose, sucrose) contained in the stem juice of sorghum as well as for the complex sugars of sorghum bagasse (cellulose and hemicellulose) [171]. Besides the production by biophotolysis of water by cyanobacteria and algae [172], biohydrogen can be produced by so-called photo-sensitive routes (photofermentation, photosynthesis) by photosynthetic and chemosynthetic bacteria, or by so-called dark fermentation by anaerobic bacteria which produce hydrogen without photoenergy. Therefore the cost of hydrogen production is 340 times lower than that of the photosynthetic process [173, 174]. The hydrogen production yield depends on the potential of a substrate for the production of hydrogen, but also on parameters such as the operating mode used (pretreatment, type of reactor, operating conditions) and the final metabolic products [84, 171]. Indeed, the breakdown of sugars during the fermentation process is accompanied by the production of hydrogen and various other metabolic products, mainly volatile fatty acids (acetic, propionic and butyric acids), lactic acid and ethanol. The production of acetic and butyric acids promotes the production of hydrogen [175, 176]. Fermentation with acetic acid gives the highest theoretical yield of 4 mol H_2/mol of hexose, while low yields of H_2 are associated with more reduced end products that is propionic and lactic acids and ethanol. The yield reported in the literature is around 10.4 L H_2/kg of sweet sorghum biomass, after 12 h of fermentation, which corresponds to an energy yield of 104 kJ/kg of fresh biomass and 400 kJ/kg of dry sorghum [84]. Although dark fermentation processes are less expensive, but only result in partial conversion of organic matter. This is why the technico-economic profitability of this process can only be envisaged by combining the production of hydrogen with a recovery of these metabolic by-products in the form either of additional hydrogen (photofermentation, microbial electrolysis cells), or of methane (methanization), or molecules with higher added values (bioplastics, ethanol, biolipids) by biological transformation, or by simple extraction of these organic acids [171]. On the other hand, one of the main disadvantages of using hydrogen is the difficulty of obtaining a reliable storage system, especially in automobiles. However, this problem could be overcome by the use of metal hydrides and carbon nanotubes, which reversibly adsorb hydrogen at room temperature and low pressures [177–179].

Thermochemical Process Energy Recovery of Sorghum Stems

Thermochemical biomass energy recovery is a dry conversion technique combining several processes based on the degradation of biomass molecules under the effect of heat. We can distinguish direct combustion (which is responsible for more than 97% of global bioenergy production), pyrolysis, gasification and liquefaction [180, 181]. Each of these processes takes place through a succession of operations requiring a whole transfer of heat on a sample of solid biomass to produce energy carriers in liquid (pyrolytic oil), gaseous (H_2, CO, CH_4, CO_2, etc.), and solid (biochar) forms. Low lignin contents are not particularly sought after for thermochemical conversion of biomass.

Direct combustion uses sorghum biomass (stem, bagasse) as solid fuel in furnaces and boilers to generate thermal energy (heat or steam) used for various industrial applications including the production of electricity by cogeneration [182, 183]. However, these power generation systems have low overall efficiency and emit large amounts of pollutants [184]. In addition, there are many operational and environmental challenges associated with biomass combustion technology. We can distinguish the low bulk density of agricultural waste (about 5 to 10 times lower than that of coal), the high moisture content, the low melting point of ash and the high volatiles content. The majority of these problems can be solved by biomass co-combustion systems [185]. In order to improve the energy efficiency of burning sorghum stems, the densification technique is often applied to biomass to form pellets and briquettes, which are products characterized by high calorific value [186, 187]. On the other hand, combustion is more efficient with more lignified biomass, because lignin increases the amount of potential energy in the biomass [182].

Pyrolysis is the thermal decomposition of biomass under the action of heat, in the total absence or in the presence of a very small amount of oxygen (air). This results in the formation of products such as bio-oil, biochar and synthesis gas, the proportions of which vary according to the operating mode, in particular the temperature conditions of the reactor, the heating rate, the residence time, the nature and size of the sample and the type of experimental pyrolysis tool used [188]. Pyrolysis is divided into conventional (slow) and fast (flash), depending on the operating conditions, (time, heating speed) [189]. Slow pyrolysis takes place at low or moderate temperatures (400–500 °C), with a long residence time (several hours), the product obtained consists mainly of biochar, and low amounts of bio-oil and gas. The flash pyrolysis takes place at high temperature (> 700 °C) with a very high heating rate (> 1000 °C/s) for a residence time of the order of a few seconds, and gives 60% of bio- oil, 20% biochar and 20% syngas [190, 191]. Torrefaction is a special pyrolysis process carried out at low temperatures (200–300 °C) and anoxic conditions [192]. Fast pyrolysis is the most frequently used pyrolytic process due to its high efficiency, but requires a higher investment cost compared to slow pyrolysis. Yields range from 75 to 80% in bio-oil, and 20–30% in biochar, depending on the type of biomass [191]. Studies carried out on the pyrolysis of sweet sorghum stems and its bagasse indicate that the maximum yield of biochar (39.5%) was reached at 400 °C and a heating rate of 10 °C/min. This yield decreased with increasing temperature, due to the degradation of hemicellulose, cellulose and lignin [193, 194]. On the other hand, the bio-oil yield first increased up to 15.94% (at 450 °C) and then decreased due to cellulose degradation and the formation of non-condensable and volatile gases, respectively. Another study conducted on the roasting of sweet sorghum bagasse showed that the yield of roasted products was 51 to 70%, and as the roasting temperature increased from 250 to 300 °C, the yield of biochar decreased while that of liquid and gas increased [195].

Gasification is a thermochemical conversion of biomass into synthesis gas (mixture of CO_2, CO, hydrogen and gaseous hydrocarbons), biochar, ash and tar by partial thermal oxidation [196]. Oxidizing agents can be pure O_2, air, steam, CO_2, or their mixtures. The biomass gasification process includes drying, pyrolysis, oxidation and reduction. The quantity, composition, and properties of the gasification products vary depending on the experimental conditions [197]. The performance of the gasification process depends mainly on the type of biomass and the air flow [198]. Gasification offers great flexibility in the raw materials and fuels produced, therefore it is considered to be the most promising technology for clean and renewable energy production. According to Stamenkovic et al. [191], synthesis gas has a low calorific value (around 4 to 6 MJ/Nm^3) and can be burned directly or used as fuel for gas engines and turbines or as a raw material for chemicals production [199]. Experiments carried out on the gasification of sorghum stalks gave a tar content of 2.2 to 3.0 g/m^3 and synthesis gas composed of 7.9 to 8.8% hydrogen, 13.1 to 15.2% CO, 15.0 to 18.9% CO_2 and 2.2 to 2.8% methane and low calorific value (3.53 to 3.90 MJ/m^3). The yield of biochar was approximately 12% and its calorific value was 4.2–9.4 MJ/kg, depending on air flow [200].

The conversion of biomass by thermal liquefaction occurs at lower temperatures (200 to 400 °C) and higher pressures (5 to 20 MPa) and in the absence of oxygen, often resulting in high yields of bio-oil and low yields of biochar compared to pyrolysis [191, 201]. The process of liquefaction includes depolymerization, decomposition and recombination reactions [202]. Temperature and reaction time are major parameters that influence biomass conversion and product yields [201]. The main products of the conversion of biomass by liquefaction are an oily and viscous liquid known as bio-oil or heavy oil, an aqueous product called light oil, a solid residue (biochar) and gases [203]. Heavy oil can be used as a raw material for fuels and polymeric, aromatic, lubricant and asphaltic products [204]. However it must be improved before use as a liquid fuel [205]. Light oil is used successfully for the conversion of water soluble carbohydrates from liquefied biomass to liquid alkanes and hydrogen [206]. Bi et al. [207] studied the production of bio-oil and biochar via sweet sorghum bagasse liquefaction previously pre-treated using both homogeneous and heterogeneous catalysts. They indicate that the best catalyst (K_2CO_3) provided a bio-oil with a higher calorific value of the order of 33.1 MJ/kg, with a high carbon content (73.2%) and low nitrogen and sulfur contents (7.7 and 0.2%, respectively). The yield of bio-oil from the sweet sorghum stalk was about 10% higher than that obtained from the stalk of corn or poplar and the yield of gaseous product increases with increasing liquefaction temperature.

Future and Innovative Insights of Sorghum and Its By-Products

In addition to its food and energy use, the lignocellulosic biomass of sorghum is also used for industrial or artisanal purposes, for biomaterials manufacture like bioplastics and bio-composites, widely used in the automotive sector and in the construction field [32, 33]. The principle is based on the addition of lignocellulosic biomass in a matrix which can be a synthetic polymer (for bioplastics) or cement (for bio-composites) in order to optimize the consistency and the mechanical and thermal resistance of the material [208]. This addition of biomass presents multiple physico-mechanical (resistance, weight, plasticity, porosity, etc.), ecological and economic interests [32]. In addition, the fermentable sugars contained in the sorghum stems juice can also be used as a raw material for the industrial production of lactic acid by *Lactobacillus sp*. [209], acetone-butanol by *Clostriduim acetobutylicum* [210], and for other organic acids production [43]. Dried sweet sorghum stems were also valorized as feedstock for direct electricity generation in a two chamber microbial fuel cells (MFCs) using anaerobic sludge as inoculum. The total electrical energy per gram of dried sorghum stalks was 165 J/g and the maximum voltage of 546 mV has been obtained with a maximum power- and current density of 131 mW/m^2 and 543 mA/m^2, respectively [211]. There are other industrial uses of sorghum by-products, which require selection of particular varieties. Thus, the variety of sorghum known as paper sorghum, the stalk of which is rich in fiber, is used for the production of paper pulp or construction panels; starchy grain sorghum used to make glues, adhesives or dextrose [20]. Dyeing sorghums, whose stems and leaves are rich in anthocyanin pigments, after grinding and maceration, give a red dye used in tannery or in pottery to tan the skins [60]. These pigments taken from dye sorghums are also used in cosmetics for hair coloring. To this end, there are 659 species of sorghum used as dyes or tannins, with 116 species of which this is the primary use [53].

Conclusion

In the current context marked by climate change, the world population increase, and the reduction of natural resources, developing inclusive and sustainable agricultural system for existing and new crops is one of the most important measures to reduce dependence on fossil resources and to mitigate greenhouse gases emission. Sorghum crops presents interesting profile to meet this challenge and its cultivation is becoming increasingly important around the world due to its rusticity, high potential for biomass production, low input requirement ant it is well-adapted in regions where the extreme agronomic and marginal conditions are not suitable for most common crops grow. Sorghum has agronomic characteristics suited to hot and dry climates as well as tropical and temperate climates. This food crop offers better yields in growing environments subject to water and heat stress and requires few inputs, allowing the valorisation of marginal lands to increase its sustainability. Mainly cultivated in Africa (where sorghum by-products are less valued) with 67.8% of the world's average acreage devoted to this cereal in 2020, sorghum is cultivated in all over the world and offers a great genetic diversity to explore and exploit. It remains one of the most versatile cereal crops used as a source of food and feed; energy source; and raw material in various industrial or artisanal applications as well as for biomaterials manufacture. Unlike other cereal crops, all parts of sorghum (its grain, sweet and juicy stem) are recoverable. This versatility as well as its high phenotypic variability have led to the emergence of new ways of valuing by-products resulting from the exploitation processes of this crop, making sorghum an ideal crop to fight against the decrease in natural resources, climate change and competition between food crops and energy crops. The reconciliation of starchy grains production and a wide variety of valued by-products in several fields of application is a particularity of sorghum which makes it more attractive compared to other cereal crops. Because of its multifunctional character allowing to combine different food, energy, and industrial uses, sorghum has become a primordial crop throughout the world. Its high production yield of lignocellulosic biomass with biochemical composition suitable for various uses, is a major asset in the current context where the challenge of energy transition and environmental preservation is increasingly worrying. Therefore, it would be interesting to reconsider the role of sorghum in the global economic system. Sorghum should be positioned as a viable alternative for sustainable economic development in the future, compared to other large-scale crops such as wheat, rice, maize, sugar cane and beet.

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Declarations

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